Manufacturing of turbines (gas, steam, hydro and wind)

Dr. Sunny Zafar

School of Mechanical and Materials Engineering

Indian Institute of Technology Mandi

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Lecture 17

Welcome to this course on manufacturing of turbines. So, in this lesson 17 of this course, we will see the material requirements for steam turbine blades. The outline of this lesson will be primarily revolving around material requirements for steam turbines, in which first we will see the application of steam turbine specifically used in the power plant. how the steam turbine efficiency is dependent on the operating temperatures. Then we will also understand the overview of the operating cycle of steam turbine. From there on we will move on to the material selection of the steam turbine blades and also look at some of the manufacturers of gas and steam turbines in the globe.

So steam turbines are very popular in energy generation sectors. So these are not only used in fossil fuel based power plants, but they are also used with nuclear power, where we have the generation of steam and this generation of steam can take place by either burning fossil fuels like coal or it can also be by the nuclear reaction that is the fission reaction and use of steam turbines has been there from a very long time. Now to increase the efficiency of the steam turbine based power plant, the steam turbines are always used in tandem with respect to the pressure at which they are operating. So, popularly three stages of pressures are used to increase the efficiency of steam turbine based power plants.

So, in this we can see here the outline of the steam turbine power plant. wherein we have the steam inlet on the left hand side. So, this steam inlet on the left hand side is coming in from the boiler. Boiler can be powered using nuclear based energy, fission based energy or it can be powered by burning some fossil fuel like coal or natural gas. So once the steam is entering into the turbine section of the power plant, so the pressure of the steam is very high.

So the steam first interacts with the high pressure stage of the turbine. So, after losing on some energy here and giving it to the high pressure stage turbine, the steam is then allowed to move to the intermediate pressure stage turbine, which is also another steam turbine. But here what we will observe that the size of the blades is slightly more because as the pressure drop takes place so we need more blade area for effective energy conversion. And from there on we move to the low pressure stage turbine where in we can see the blade size it is further increased compared to the intermediate or high pressure stage and after that the steam is exhausted out it can be taken to the condenser and the waste heat extraction or recovery can be done. And from the turbine, all these turbines are then subsequently connected to a generator and the generator is used to generate power or electrical power.

So, if you try to understand the efficiency of the steam turbines, so the efficiency of the steam turbines is also dependent on the thermodynamic cycle based on Rankine cycle. So, the Rankine cycle is the thermodynamic cycle. on which the steam turbine power plant is operating. So, in this Rankine cycle, we know that the pressure as well as the temperature, it plays a very important role on the final efficiency of the turbine for converting the energy of this high pressure steam into rotation. So, in the initial years, the steam turbines, they were operating in the subcritical range, which is on the left hand side.

So, in the subcritical range, we could have working parameters of temperature that is 540 degrees Celsius and the pressure of around 14.5 megapascals. And because of these operating conditions, the overall efficiency of around 37 percent was achieved and this subcritical technology was much mature and was quite stable for a long period of time. To further increase the efficiency of the steam turbine power plant and take it to of the order of 45, around 45, 40 to 45 percent. the operating temperature was increased to 600 degree Celsius and the operating pressure was almost doubled, it was around 28 megapascals.

So, we call this technology as supercritical range or the supercritical technology in which operating conditions are made such that the efficiency reaches 45 percent. And this technology is currently widely used in several steam based power plants which are established. And now going forward to further enhance the efficiency to up to 60 percent, the overall efficiency should go as high as 60 percent. It is desired that the steam power plants are set up in the ultra-supercritical range. And in the ultra-supercritical range, the temperature should go up to 760 degrees Celsius and the operating pressures should be around 35 megapascals.

Now, with this even 1 percent increase in efficiency of the steam based power plant, we can decrease the carbon dioxide emissions of the order of 1 or 10 lakh tons over a lifetime of a typical 800 megawatt power plant. So, to increase this efficiency even by 1 percent, so of course, there are several parameters which go into increasing the efficiency. But from the aspect of this course, we look at what new materials are developed to manufacture the steam turbines and to utilize those materials to create the steam turbines or steam turbine blades which manufacturing processes are specifically used and which result into the more efficient steam turbines. So, now we will understand the various components of the steam turbine. So, steam turbine it is a rotary engine or is a rotating machine which extracts energy from pressurized steam.

The key components in any steam turbines are these three key components which include rotor, stator and nozzle. So, rotor is basically a central shaft with rows of precisely shaped blades mounted around its circumference. The stator is also a stationary casing containing another set of fixed blades. which are positioned strategically to guide the flow of steam. So, this alternating layer, alternating sequence of rotor and stator blade ensure that maximum energy is converted from the steam flowing over the blades into rotation and then we have a nozzle.

It is a convergent passage which accelerates steam to increase its velocity and kinetic energy. So, these three components are generally housed in a casing. And inside the casing, the only steam is allowed to pass. And on the right hand side, we can see image of a steam turbine blade. So, we can see these rows of various blades which have sequence of rotor and stator.

So, next we will understand overview of the thermodynamic cycle on which the steam turbines are operating. So, the steam power plant is operating on Rankine cycle. So, in the Rankine cycle, there are four important components. So, the Rankine cycle starts with the isentropic pumping of water from point 1 to 2. So, we have a pump here.

To run the pump, some input work has to be done, so which is denoted by WP. So then this water is pumped into a boiler where heat is added denoted by QB. So this heat addition as discussed previously can take place either from fossil fuel based energy source like coal, natural gas or it can be nuclear energy. So, this heat addition in the boiler, it converts the liquid water into steam that is the gaseous state of water. This then high pressure steam from 2 to 3 actually the heat addition is taking place from 2 to 3 and then this high pressure steam is allowed to expand from 3 to 4 over this turbine.

This is the steam turbine. and as the steam, it expands over the steam turbine. So, work output is there denoted by WT and then the exhaust steam is taken back to the condenser. In the condenser, the heat is again extracted. So, condenser is nothing but it is a heat exchanger.

So, upon extracting heat from these vapors, they convert back into water. Of course, in an idealized scenario, we assume there is no loss of vapor. But in practical scenario, there may be some loss of vapor which is compensated by topping it up with more liquid water. And subsequently, the cycle keeps on repeating. So now to understand this thermodynamic cycle in stages we will see this way four main stages which in the first stage which was from point 1 to 2 is the isentropic expansion is there where high pressure, high temperature, high pressure steam is expanding through the turbine blades converting the thermal energy into kinetic energy this expansion ideally occurs without heat loss so therefore it is isentropic process.

Then is the condensation which is basically the low pressure low temperature steam while exiting from the turbine enters the condenser. And as mentioned earlier condenser it is a heat exchanger which cools down the steam converting it back into liquid water condensed water is then pumped again to a high pressure level using a feed water pump. And then heat addition is done in the boiler where external heat source may be used to add heat and converting the liquid water into high pressure, high temperature steam which is again ready to enter the turbine and the cycle can begin. So, now we come to the material selection in the steam turbine.

So, there are some key considerations while we make material selection for steam turbines. So, these key considerations in material selection, they involve three main factors. So, these factors are high temperature strength, creep resistance and fatigue resistance. So, high temperature strength is one of the prime factors of consideration while making the material selection because as we understand the technology of steam turbine is aiming towards higher thermal efficiency.

So, we anticipate increased temperature operating temperatures to which these blades must withstand and they should also not only withstand but these extreme temperatures of the order of 600 to 700 degree Celsius. So, these temperatures should also not reduce or compromise the mechanical properties of the blades especially the strength. Second important consideration is the creep. So creep is as we have seen earlier in the gas turbines also. So creep is basically failure of material or component under constant load and elevated temperature.

And in case of steam turbines, we also understand there are elevated temperature. But of course, these temperatures are not same or similar to what a gas turbine experiences. Nevertheless, the probability of creep is still there, so the material whatever is selected, it should have the ability to resist gradual deformation under high temperature and stress over extended periods. Thirdly, we use the fatigue because these blades are mounted on the turbine, which is constantly rotating. So blades experience millions of stress cycles during the operation and the material of the blade should be such that it must be able to resist cracking and fatigue.

To understand the basic structure of the steam turbine, we can look at this image on the right hand side, which shows various parts. So the steam turbine in appearance it looks quite similar to the gas turbine. The only thing which differs it from the gas turbine is of course the absence of film cooling holes and further the turbine is similar to what it looks in the gas turbine that it has an aerodynamic cross section with which we have a blade tip on the top. We have a leading edge which from where the turbine, the blade is experiencing the incoming steam and then we have a trailing edge, we have a blade profile. The blades are often twisted to create this complex geometry for maximum efficiency or to efficiently remove, extract energy from the turbine which gives this inner arc and the carry arc shape.

And at the bottom, we have the blade roof which is again a dovetail sort of a shape which is helpful in mounting the turbine blade on the rotors. So the key considerations of other key considerations in the material selection they also involve the presence of operating challenges such as oxidation resistance because this steam whatever is flowing it is again the gaseous form of water and steam as we know is reactive to some blade materials especially with at high temperature which can cause surface degradation and weakening corrosion is another important challenge, because we are dealing with moisture and contaminants in the steam and which can cause corrosion especially on the leading edges of the blade which may cause deterioration Then we have also understood the complex profile of the blade with this twisted curve shape to which the material whatever is selected it should be able to machined to fabricate complex blade shapes without excess difficulty and cost. And lastly we have to also balance the cost with desired material properties along with the economic considerations by manufacturing of the steam turbines. So, if we look at what materials are used or popularly used these days to make the steam turbine. So, these are essentially the alloy steels of different types which are used to make the steam turbines.

So, as we have seen in case of gas turbines, it was a nickel based super alloy because the nickel based super alloy is able to retain its strength and other mechanical properties at elevated temperature. Similar properties are also desired here in the steam turbine but here the extent of operating temperatures are not as high as the gas turbine. Therefore, the use of these high alloy steels which are mostly chromium nickel based steels and sometimes molybdenum etc may also be added for high temperature stability. These are used to manufacture the steam turbine blades.

So, these involve carbon steels. carbon molybdenum low alloy steels, 9 to 12 percent chromium steels, 18 percent chromium, 8 percent nickel steels, 15 percent chromium, 8 percent nickel steel, 20 to 25 percent chromium based austenitic steel, high chromium and nickel based steel. So, mostly we will see steels in which predominantly we have chromium and nickel added for high temperature stability and corrosion resistance. are the material of choice in steam turbines. So, if you understand the relative material costs along with the operating conditions of the steam turbine, it is not that we cannot use the inconel or nickel based superalloys, but as the conditions which are there in operation of the steam turbines are not as severe as it is in the steam turbines. So, use of this chromium nickel based steels is sufficient.

And of course, some new materials are constantly developed because if you look at this graph here, what is observed that above 700 degree Celsius of temperature and between 800 degree Celsius of temperature, so there are very less materials which are there in this band. Of course, beyond this we have the nickel base superalloys, but it may not be economically feasible to use the nickel base superalloys in making the steam turbine blades because cost of manufacturing of nickel base superalloys is much higher than cost of manufacturing with chromium nickel waste steels. So, traditionally these 9 percent to 12 percent chromium steels are used and as the temperature is increasing, so the percentage of chromium and nickel is increasing. So, this 18 percent chromium, 8 percent nickel steels are used. And as we approach nearing 700 degree centigrade, so what is observed that 20 to 25 percent based austenitic grade steels are used to make the steam turbine blades.

But there is a gap in material development and as the temperature range of the steam turbines, they go beyond 700 degree Celsius or it is between 700 degree Celsius to 800 degree Celsius that is the ultra supercritical range. Newer materials are being constantly developed for such applications. So, next if you look at the various components which are used in the steam turbines which include the wet steam piping is made up of carbon steel, stator diaphragms casings made up of cast steel, shaft and disc made up of low alloy steel. blade and buckets made up of 12% chromium stainless steel low pressure rotor blades these are made up of martensitic stainless steel. Stationary blades or that is the stator blades made up of austenitic grade stainless steel and the high pressure blades expansion bellows are made up of austenitic grade stainless steel other steels which these are the high alloy steels which offer a good balance between strength creep resistance and cost effectiveness So these are oftenly used in the low pressure and intermediate pressure turbine sections.

Examples include 4145, 4340 steels and because of this well established use of such steels they are readily available and machinable. Nevertheless, such steels also have certain limitations that at lower high temperature strength compared to the nickel-based superalloys and they may also not be suitable for high pressure sections of the steam turbine. Some of the component in the steam turbine may also be made up of nickel-based superalloys which as we understand from our previous discussion on gas turbines, they are able to retain high strength and creep resistance. and they also offer good oxidation resistance and could be used in advanced turbine designs. Nevertheless, their high cost and difficulty in machining complex configurations and may also need specialized welding techniques are some of the limitations while using nickel based superalloys.

Now we will look at the emerging materials which are used in steam turbines. So whatever materials are talked before are the conventional materials are widely used in industry. But to fill in the gap between say 700 degree Celsius to 800 degree Celsius to create ultra supercritical steam power plants, newer materials are constantly developed. Among them, these are two popular materials, which are based out of ceramic matrix composites and directionally solidified alloys, which offer exceptional high temperature strength and low weight. Additionally, the directionally solidified blade is a single crystal structure, which provides superior creep resistance, but may need complex manufacturing processes.

For example, if we just summarize the manufacturing process of silicon carbide based turbine blade. So, this starts with the silicon carbide fiber, which is then done a CVD coating of boron nitride here. Then it is passed to silicon carbide and carbon based particulates in the solvent to create the matrix slurry to get this prepreg tapes. So, then the silicon carbide is impregnated, fiber is impregnated with polymer. Polymer is converted into carbon by high temperature pyrolysis and then what we do is basically we stack these layers, prepreg layers, do the molding and shaping using the autoclaves convert it into the carbon based matrix using pyrolysis and then basically siliconization is done in vacuum around 1420 degree Celsius.

So, the advantages of using the ceramic matrix based composites involve the outstanding high temperature strength even allowing the turbine to operate at high temperature in turbine. lower weight compared to traditional materials. This improves the turbine efficiency to a great extent and they also have good oxidation resistance. But there are certain limitations like brittleness, high machining cost and limited machining options because these are extremely hard. So, to create complex shape, we have very limited options to create the machinability to create such blades using ceramic matrix composites.

Regarding the directionally solidified alloys, so it is a costly proposition because they have limitation of high cost and design limitations are also there because single crystal structure can limit the design flexibility. And they may need again very specialized casting techniques which may increase the overall cost of the materials. So now we can have a look at this list of some of the world leading companies which make the steam turbines as well as the gas turbines. So these are the companies in which these products are manufactured.

So with this we come to the end of this lesson. We will now summarize what we have covered. So we have covered regarding the steam turbines in this lesson. in which we have looked at the operating thermodynamic cycle that is the Rankine cycle. We have looked at material requirements for steam turbine We have seen all the materials used in steam turbine manufacturing and we have seen some trends in material development. which involves utilization of ceramic matrix composites and directionally solidified alloys.

Lastly, we have looked at names of some manufacturers, popular manufacturers for gas and steam turbines. In the next lecture, we will start in detail the manufacturing processes for steam turbine starting with the primary shipping that is the investment costing route for making the steam turbine.

Thank you.