Turbomachinery Aerodynamics

Prof. Bhaskar Roy
Prof. A M Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. # 02

Axial Flow Compressors and Fans

Introduction to Compressor Aerothermodynamics

Hello and welcome to lecture number 2 of this lecture series on Turbomachinery aerodynamics. So, in the last lecture, we have just had a very quick introduction to this particular lecture series that you going to undergo, and we also had discussion on various topics that we are going to discuss during this courses; we had a quick look at the lecture schedule in terms of lecture wise topics, which are to be covered; and subsequently we also discussed about the different types of machines are turbo machines, so-called turbo machines that we are doing take up in this lecture series.

I think you must have realized by now this significance of this kinds of course, which is relatively very specialized course, the basic reason for this kind of a course being offered, is the fact that turbo machines as we know it in either in the compressors or in the turbines, which is what we going to discuss in this courses, is extensively used in day today life; one of the most common application of this being the compressors and turbines used in gas turbine engines and aircraft engines; and therefore, compressors and turbines, the turbo machines form one of the most important components of jet engines; besides this of course, these components are also present in land based power generation units.

The thermal power plants, which use gas turbine engines for generating power, they also have turbo machines like the fans, compressors and the turbines; which means that there is a substantial or a significant application of all these components, which is the reason why such a specialized course is being offered, which discusses primarily the aerodynamics associated with the turbo machine components. So, in today's lecture we are going to discuss about the compressors and fans; we will have a quick discussion on the simple aerodynamics of compressors or and fans, and how is that we can account for the aerodynamic performance using very simple analytical tools. So, we are going to have a very quick over view of some of these topics; we will also be discussing about some of the analytical methods, which are used in very preliminary design, analysis, techniques which is what one would endeavor, before taking up a very detailed component performance or component design. So, in today's class, we are going to discuss about the following topics.

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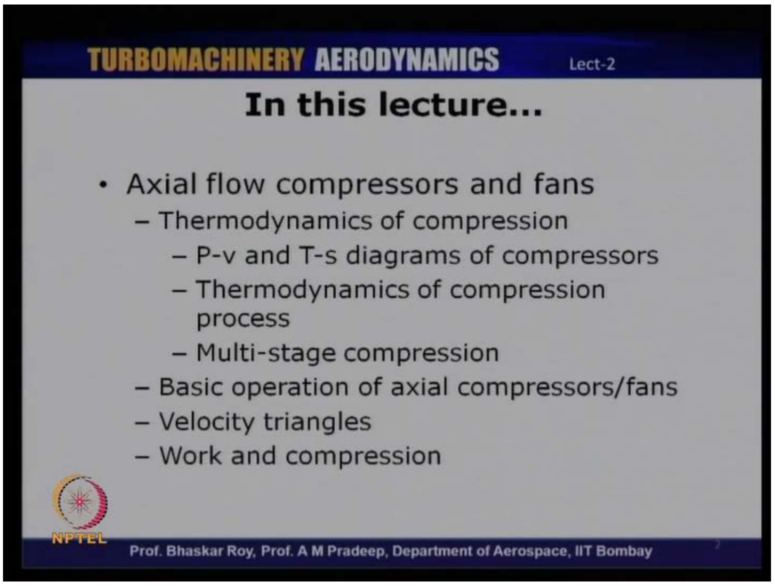

So, we going to talk about the thermodynamics of compression, its very important that we understand, the fundamental thermodynamic principals behind compression; we will express the compression process in terms of pressure volume that is P-v and temperature in trophy T-s diagrams of compressors, and subsequently, we will take up the compression process, and how compression takes place in single stage as well as multi stage compressors, we will express the compression process in terms of the temperature entropy diagrams; and then we will begin our discussion on the basic operation of axial flow compressors and fans; subsequently, we will take up a very important concept, which is known as velocity triangle, which forms the basic analytical tool for analysis at a very simple design operation, which is what one would start off with before taking up detailed component design; we will also be talking about work and compression, how we can calculate the compression ratio in a compressor using the temperature rise across the compressor and so on. So, we will derive an expression for calculating the work that is required for driving a particular compressor for a certain pressure ratio.

So, these are some of the topics that we going to discuss. So, you you have seen that we going to begin our talk with a discussion with very simple analytical methods, and so, we need to understand, what is the significance of these analytical tools? Why should we even go for very simple analysis, which invariably have a lot of assumptions inherent in them, which may or may not be really true in an actual compressor; but these analytical methods are very important in terms of actual design, because this is where an actual design starts.

So, when we take up a compressor design exercise, we start the design process using very simple analytical tools. So, basic idea being behind carrying out such an analysis is that we can get some idea about what is the kind of power that or work that will be required to drive this particular compressor for a certain pressure ratio. We would also get some estimate about what are the kinds of losses that this compressor is likely incurred; and therefore, the efficiency of such a compressor system. So, the advantage of this analysis is that it gives you a very quick design optimization process, where in you get a very preliminary design of a compressor, and from which you can also estimate the power requirements, and therefore the efficiency and so on, and if that that does not really fit in this scheme of things, one can incorporate certain design changes to ensure that the compressor actually meets the specifications, for which it is being designed; and so, this is the primary objective of carrying out this kind of a simple analytical technique.

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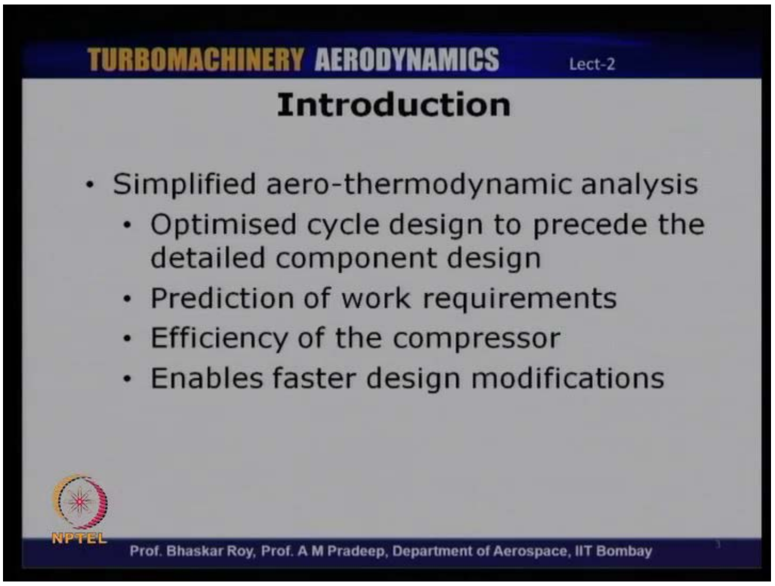

And So, which means that a simple aero thermodynamic analysis, which basically precedes a detailed component design, is something which is required to have a reasonably good prediction of work requirement as well as the efficiency of the compressor, and the main advantage being that this enables very quick design modifications, because if one word to take up detailed design, right at the beginning and at the detail design obviously, is much more complicated and it takes a lot of time and effort, and lets say at the end of that exercise, we we see that the the compressor requires certain modifications to meet the design specifications; then the design turnaround time is is is quiet huge, because it takes a lot of time for carrying out detail component design; therefore, a simple aero thermodynamic analysis will give us very quick idea about where this compressor is taking us if if it is a a good compressor, in terms of efficiency and bulk requirement, then we can proceed further and take up the detailed design. So, there that means that it saves a lot of time in terms of the overall design and optimization cycle. So, that is the basic need for carrying out such a simple aero thermodynamic analysis.

So, what we are going to do is that we will begin with very simple thermodynamic concepts, which had presume, you would have undergone during some of your earlier courses, we will take a look at a compression process in strictly a thermodynamic science, that is what happens in an ideal thermodynamic compression process, and what happens in an actual thermodynamic process. So, that is what we will begin with a discussion on how we can analyze a compressor in terms of its thermodynamics process of compression itself.

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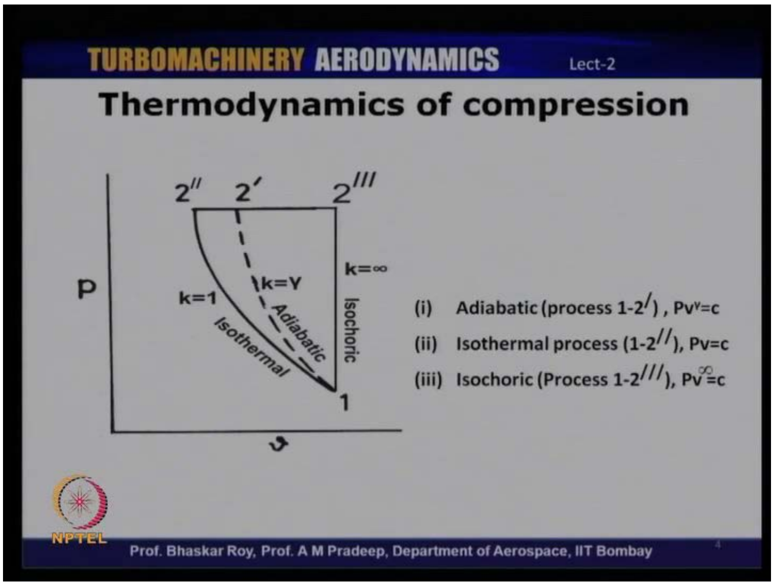

So, what I have here is a simple representation of a compression process, you can see that, on the left hand side the graph here is expressed in terms of pressure and volume, which is specific volume basically; and you can see three different lines or graphs, here 1 to 2 dash, 1 to 2 double dash, and 1 to 2 triple dash; each of them representing a different type of compression process; the first process that you see that is 1 to 2 prime is an adiabatic compression process; an adiabatic compression process is one where the exponent that is involved is P v rise to k, here in this case, the exponent is equal to gamma, which is the ratio of specific heats. So, this is an adiabatic compression process, and what we will see is, very soon is that an idealized compression process, can be expressed as an adiabatic compression, which is reversible; which means that if you remember from your thermodynamics, a reversible adiabatic process is an isentropic process. So, if the adiabatic process can also be approximated to be a reversible process then what you have is an isentropic process that is the entropy remains a constant. So, on a temperature entropy diagram, one would get a vertical line, which basically indicates that the entropy is a constant.

So, this is true for an adiabatic process where k is equal to gamma. So, this is basically a process, where we have the power of the product P v rise to k is equal to gamma, and that is that represents an adiabatic process. Now let us take a look at the second process here, where k is equal to 1 that is the exponent is equal to 1, which means that it is P v rise to 1, which is P v is a constant; the product of pressure and volume is a constant and what is that indicate? It basically tells us that pressure the product P v being constant means that this is an isothermal process that is temperature remains a constant during P v is equal to constant process.

So, the second process of compression, again as I mentioned all these three processes that we are discussing is a compression process, basically because the pressure is increasing, because compression is accompanied by in increase in pressure, and also by a decrease in specific volume. So here, we have one of the processes, the first process is which we discussed was an adiabatic process, P v rise to gamma is constant; the second process is an isothermal process because P v is equal to constant. So, because from the state law, if you remember P v is equal to r t, and so since P v is constant the right hand side r t, the gas constant is any way constant, and therefore, temperature also remains constant, and that represents an isothermal process; and the third extreme of this is, if v is equal to 0, that is if specific volume is equal to 0, you get an isochoric process that is volume is a constant, but you still get the pressure rise and that is the third process.

So, out of these three, I think the first two that is an adiabatic process and an isothermal process is what is of interest to us; the reason being in an isentropic process as you know, if it is reversible, you have hardly any losses taking place; if it is a reversible process there are no losses, so the efficiency of the compressor is very high; and this the second possible process is an isothermal process, you might have studied about inter cooling in your thermodynamics course, inter cooling is a process where at the end of one compression process, you cool down the air to its initial temperature, before taking up the second compression process and so on.

So, number of stages of inter cooling can lead to a compression process, which is isothermal; advantage of an isothermal compression is that isothermal compression requires the least work input, you might have seen in your pressure volume diagram; area under the curve tells us the amount of work required for this particular compression process, and therefore an isothermal compression process requires the least work, and that is the basic advantage of having an isothermal compression process, but all the actual cycles cannot really be taken up as an isothermal compression, because there is an increase in temperature taking place during the process, it is never P v is equal to constant; it is always P-v rise k is equal to constant, but for our simplified analysis most of the time you might assume that the exponent is equal to gamma, and therefore P-v rise to gamma is equal to constant that is an adiabatic compression is a much more realistic type of compression process that one might deal with in day to day life.

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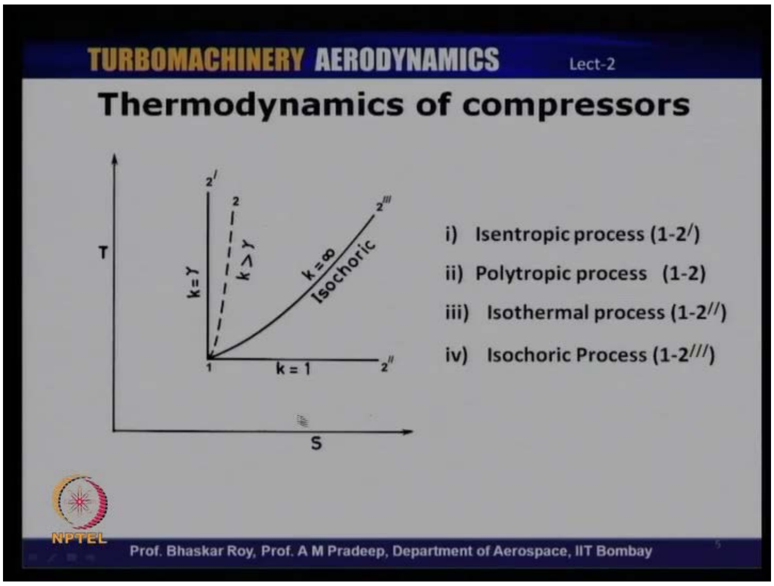

So, let us move forward now; let us express the same processes on a temperature entropy plot; I mention that one of the processes has k is equal to gamma, which is an adiabatic process, and if that is a reversible process, then we have a nice entropic process. So, that is the first process that is being represented here, when k is equal to gamma, the compression represents an isentropic compression, which is why you have a vertical line, because your x axis is entropy. So, this is the constant; so you have a nice entropic compression; and in actual cycles, you would not really have the compression, which is adiabatic, so you may have gamma which is different from that of specific heats may be different. So, you may have a non isentropic compression.

So, this is represents, the dotted line actually represents the polytrophic process where the exponent is not necessarily equal to gamma; and then we have the other extreme that is 1 2 double prime, where k is equal to 1, this is an isothermal process therefore, temperature is a constant. So, you can see that the temperature is constant of course, it is non isentropic, but this is an isothermal process; and you may also have k is equal to infinity, which is basically corresponding to an isochoric process that is the constant volume process. So, this is the thermodynamic representation of compression on a temperature entropy diagram T-s diagram, what we have seen previously was pressure volume diagram. So, one can express the compression process in either temperature entropy coordinates or in pressure volume coordinates.

So, you going to come up with, we will be looking at compression process throughout this course, in either of these coordinates, either pressure volume coordinates or in temperature entropy coordinates, but most of the time as you would notice very soon, we would be usually using the temperature entropy diagram; basically because of the fact that it is it will easier to visualize adiabatic processors and non or isentropic processors and non isentropic processors on a T S coordinate, and therefore we will usually be representing the compression process on a T S k or T S coordinates; now, what we will do next is that we will also start looking at the compression process itself, not just in terms of t v P-v or T-s diagrams, but also in terms of what happens in an actual compressor, and how the pressure rise or temperature rise takes place across rotors and stators of an axial compressor.

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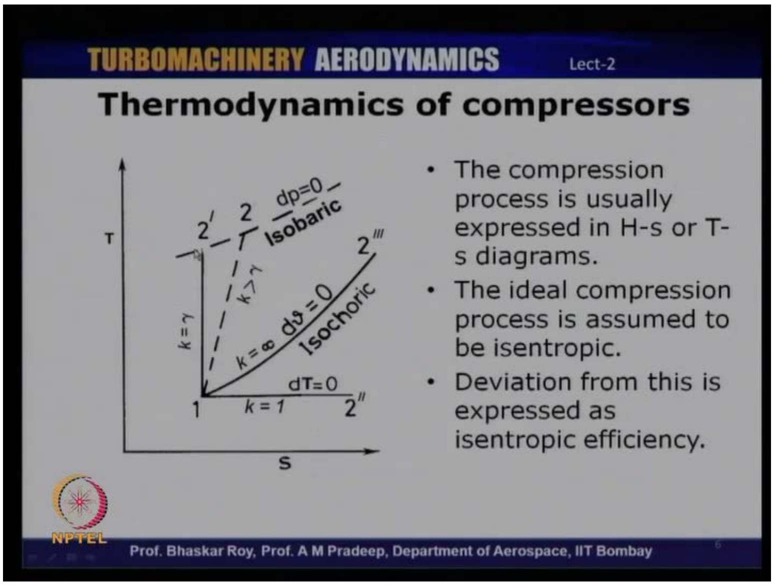

So, before that lets again look at this temperature entropy diagram. So, here we have T-s diagram, which is what I had shown in the previous slide. Now, in an ideal process, as I mentioned, we would normally assume the compression process to be this that is k is equal to gamma, which is 1 2 prime that is an isentropic process, and an actual compression process is what is represented by the dotted line, where k may not be equal to gamma, it could be different from, it could be a polytrophic process, which is 1 2. So, this represents an actual compression process 1 2, ideal compression process is 1 2 prime. So, the deviation of the actual compression process from the ideal compression process is usually expressed in terms of, what is known as an isentropic efficiency.

So, enthalpy at state 2 prime minus enthalpy at state 1 divided by enthalpy at state 2 minus enthalpy at state 1 represents what is known as an isentropic efficiency of the compressor; because that tells us how far is the compression operation from an ideal behavior, because if it was an ideal behavior isentropic efficiency would have been equal to 1, and you would have got a vertical line, which represents an isentropic process. So, actual compressors are obviously, not isentropic. So, the deviation of actual compressors from the ideal compressors is usually expressed as isentropic efficiency of the compressor system. So, we shall be referring to isentropic efficiency very often in throughout the codes, because that forms one of the basic parameters or performance measures using with, we will evaluate the performance of compressors. So, it is very important to understand the significant of isentropic efficiency.

So, moving ahead what we will do next is to look at what happens in a compressor rotor and a stator combination, as you are aware that a stage of a compressor, an axial compressor let us say, consist of a rotor followed by a stator; rotor is the rotating component, stator is the stationery component. So, in a in a compressor, if you look at one stage of an axial compressor, you would you would basically have one component, which is rotating that is called the rotor, this is followed by a stationery set of blades, which are known as stators. So, let us take a look at what happens to the flow as or thermodynamically what happens as the flow passes through a rotor and subsequently through a stator.

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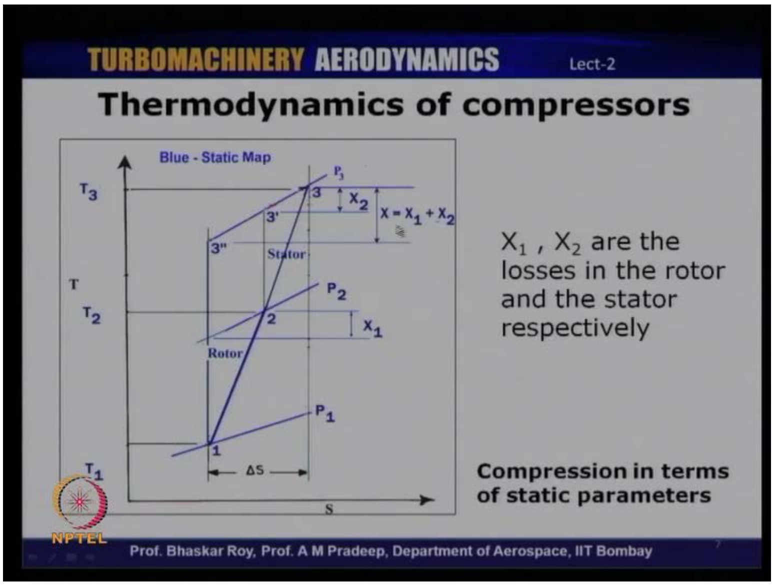

So, what I have here is a temperature entropy diagram, which represents the compression process in terms of lets first look at the static parameters that is, we are looking at static temperatures here and static pressures. So, this represents the rotor, and then subsequently, we have a stator. So, state 1 indicates the rotor inlet, state 2 indicates rotor exit, state 3 indicates rotor the stator exit; now the vertical lines here, actually show the isentropic processes that is if the entire compression process was to be isentropic, then one would have got a change in temperature from state 1 to state 3 double prime; now since there are losses taking place or irreversibly it is taking place in the rotor as well as stator.

We see that the line at the compression process is not isentropic, it is non isentropic which is why we can see this inclined line, which means that the reason increasing entropy, which is both across the rotor as well as the stator. So, 1 2 represents the actual compression in the rotor, at the exit of which the temperature is T 2, static temperature is T 2, and static pressure is P 2; from state 2 to 3 is the stator, at the exit of the stator we have static temperature T 3, and static pressure P 3; now if we look at this corresponding isentropic processes 1 to 2 double prime would have been the isentropic compression process the actual process is between 1 and 2. So, what is represented here as X 1 represents the loss of the loss taking place in the rotor, because of irreversibilities; similarly, there is a certain amount of loss taking place in the stator, because which is basically the difference between the actual and isentropic states, which is represented by X 2. So, X 1 and X 2 represent the losses taking place in the rotor and stator respectively.

Therefore the total loss taking place in the compressor stage is equal to the sum of the two which is X 1 plus X 2. So, what I have represented now is the compression process using static parameters, and what we will take up next is to look at the compression process in terms of stagnation parameters as well, and there you will notice that there are certain differences, which you will have to keep in mind, when you look at the variation of stagnation parameters; basically it is the fact that across a stator, there cannot be any change in stagnation temperature, because we are not hiding any energy in in the stator.

Unlike a rotor where energy is added, therefore it is possible for us to have a change or rather an increase in stagnation temperature in a rotor; on the other hand the stagnation pressure can be different both in stator as well as rotor; in a rotor, you get an increase in stagnation pressure; in a stator, because of losses taking place in the stator you might end up getting a lower static stagnation pressure, you might have the loss of stagnation pressure in the stator, and not loss of stagnation pressure in the rotor; in the rotor you have an increase in stagnation pressure as well as stagnation temperature, whereas in the stator, one has no increase in stagnation temperature, and you might have a certain amount of stagnation pressure loss in the stator. So, let us a look at the temperature in entropy diagram on stagnation coordinates.

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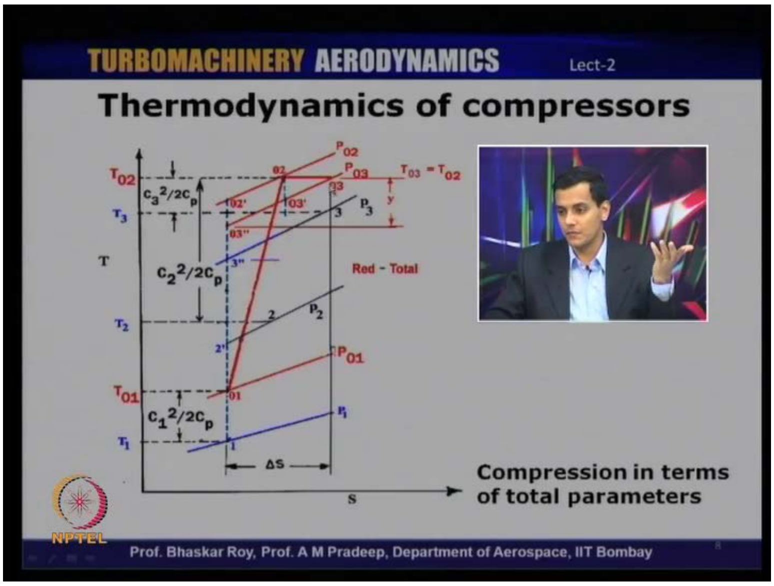

So this, in this particular diagram what is shown here in red line indicates the total parameters. So, the red lines here indicates the total parameters; whereas, the blue and black line indicates the static parameters. So, compression begins at state 1, which is static temperature, this if you add the stagnation dynamic head, you have the stagnation temperature.

So, T 1 plus C 1 square by 2 C p, where C 1 is the absolute velocity through the router by 2 C p gives us the rotor inlet stagnation temperature, which is T 01; and then after these us it after let us say the total entry, now the flow proceeds through the rotor, rotor exit is T 02, which is shown here; there is a stagnation temperature rise, as I mentioned there is a stagnation temperature rise in the rotor, because there is energy added in the rotor, because rotor is driven by a an external agent and therefore, it is possible for us to get an increase in stagnation temperature in the rotor, which is why you see that T 02 is greater than T 01, and then we have the corresponding pressures, stagnation pressure at inlet was P 01, static pressure is P 1, at the rotor exit the stagnation pressure is P 02, at the stator exit you can see that P 03 is usually less than P 02. So, I mention that in a stator, you might have certain stagnation pressure loss, because of frictional losses etcetera, but you cannot have a loss in stagnation temperature, which is why you have T 03 is equal to T 02, the stagnation temperature at rotor stator entry and stator exit remain the same, they cannot change; whereas, they can be a stagnation pressure law is taking place in the stator.

Similarly, the corresponding velocity components are shown that is T 2 plus C 2 square give us gives us T 02, and similarly T 3 plus C 3 square by 2 C p gives us T 03, which is obviously, equal to T 02. So, what is represented here in terms of what seems to be rather complicated graph is that the compression process proceeds in stages, that is you have certain compression taking place in the rotor, you also have certain amount of compression taking place in the stator, it is a combination of these two that gives us the overall compression; and so once you understand the basic thermodynamics behind the compression process, the the rather complicated diagram, which you might have seen now will really look quite simple, because even though it will it looks very complicated with all those numbers there with C 1 square by 2 C p and C 2 square by 2 C p and so on, if you understand the logic behind them.

It is very simple, T 1 plus C 1 square by 2 C p gives us T 02, and similarly the stagnation temperature is equal to the static temperature plus the absolute velocity square divided by 2 C p; and the fact that there is stagnation temperature rise taking place in the rotor, because of energy addition, stator there is no change in stagnation temperature, because you are neither adding any heat or nor taking out any heat; in the rotor, you also have stagnation pressure rise, but in the stator you may have stagnation pressure loss, which is because of the frictional effects that affect a compressor performance. So, what we have seen is the compression taking place in one stage that is in one rotor and one stator.

Let us not take a look at, what happens as the flow passes through multiple rotors and stators that is you have several rotors and stators in an multi stage axial compressor, the one which you had seen in the last class, you may have let us say 15 to 20 stages, each of them having one rotor and a stator. So, when flow passes through these rotors and stators what happens to the flow?

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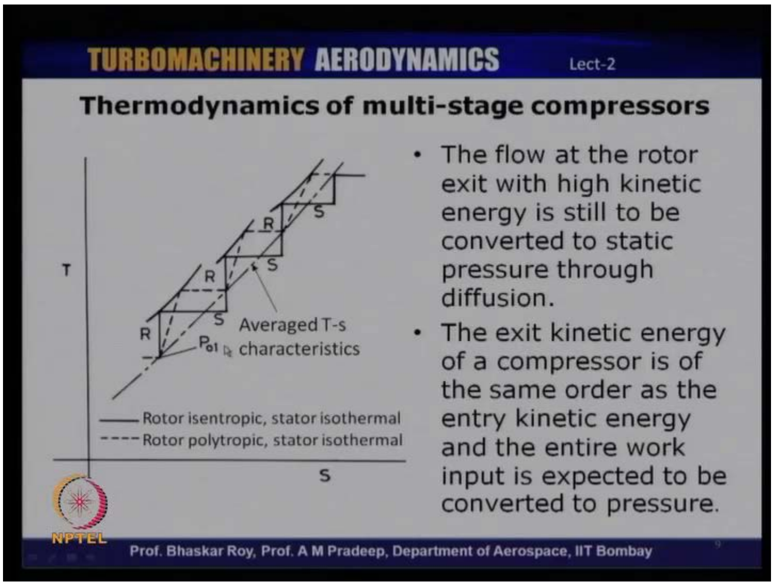

So, in a multi stage compressor, in which what is represented here in terms of T-s diagram; you have the rotor what is which is indicated by R, and stator which is indicated by S. So, what we see is that the at the rotor exit, the flow still has substantial amount of kinetic energy; this we can convert to static pressure using stators, which is why one has we would have stators, because at the exit of rotor, the kinetic energy is quite high and therefore, we can convert that to static pressure; and so what you see here is the the solid lines represent the isentropic processes that is the rotor is isentropic and there is isothermal stator, and in an actual compressor, the rotor is usually polytrophic, it is not isentropic, but the stator continues to be isothermal, because even in actual compressor, you still cannot have loss of temperature taking place in the stator.

So, an actual compression is what is shown here, polytrophic compression in the rotor followed by isothermal compression in the stator, and that proceeds for several of these compressor rotor stator combinations or stages; and what is shown here by this line here represents the average temperature entropy characteristic that is if you consider all these rotor stator combinations, the average of this represents the average behavior of the compressor, which has multiple stages of rotors and stator combinations and so, the average temperature entropy varies in a manner, which is shown by that particular line.

So, what we have done so far, is to look at the performance of a compressor from a very simple thermodynamic prospective. So, let us move a little further now, and look at the basic operation of an axial compressor itself, how does an operation a compressor operate, thermodynamically we know now how do operates, but how does the operation of the axial compressor take place in an actual sense. So, we will now look at the operation of an axial compressor itself, and then we will discuss what is known as the velocity triangle, which is a very important concept. So, we will spend some time discussing about that.

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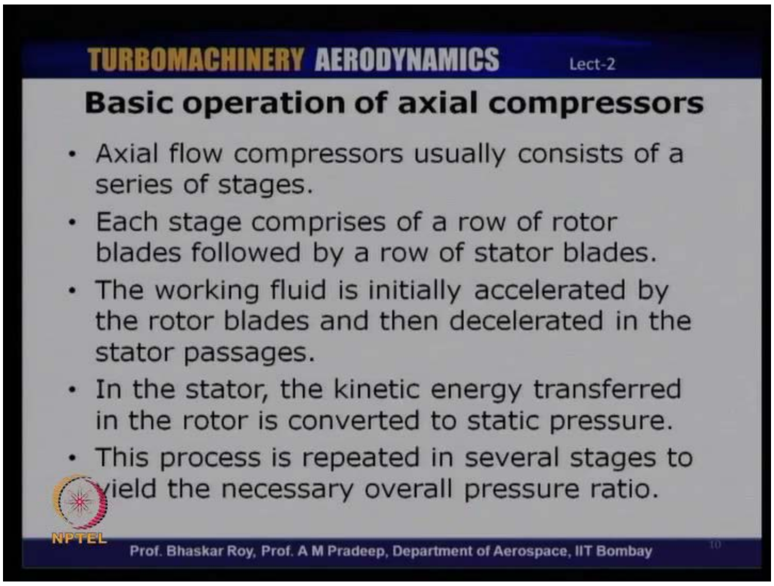

So, an axial compressor as we know consist of usually consist of series of stages and so, each of these stage has one set of rotor blades and followed by a set of stator blades. So, why do we have a rotor and a stator? Thermodynamically, we have seen the reason why? Rotor is the component through which energy is added to the compressor; so for compression to take place we should be able to add energy; and why do you need to add energy? You need to add energy, so that you get an increase in stagnation temperature, which is possible only if you add energy, you also get an increase in stagnation pressure correspondingly, because you are adding energy. So, compression can take place only if energy is added to the system, and that is why a rotor is required; then you may wonder why do we need a stator at all? Why cannot we have a only a series of rotors the reason why we have rotor followed by stator is that at the exit of the rotors, we have a substantially high kinetic energy, which is present; and therefore, if we do not have a stator, the next rotor which follows or succeeds the first rotor stage, will face a substantially high kinetic energy; that means, it has to deal with the very high kinetic energy and therefore designing such rotor is not an easy task.

A stator is meant, so that you can diffuse the flow, recover static pressure by converting kinetic energy into static pressure, decelerate it, before it hits the second rotor stage and so on. So, in a stator we basically recover static pressure by converting kinetic energy to pressure. So, that is why we have a stator, which follows a rotor; and this of course, is carried out over several stages of rotors and stators.

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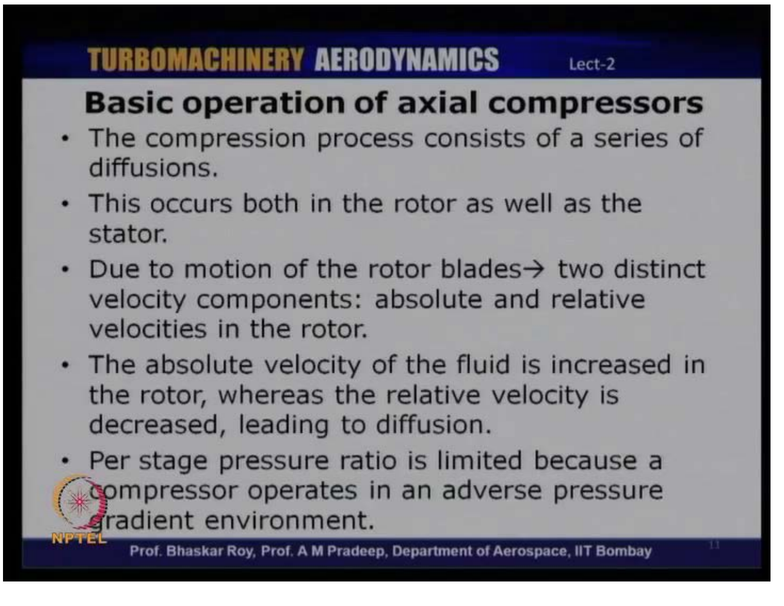

So, as we can see compression process occurs in both rotors as well as stators; and because rotor blades have a rotating motion present, we have two distinct velocity components present: one is the absolute velocity and the other is relative velocity; absolute velocity is something, which is increased as it process through the rotor, whereas the relative velocity decreases, which is why it leads to diffusion even in the rotor, and then so, which means that in an compressor stage, especially in the rotor, because of the rotor, rotation itself, you have two distinct component of velocity; one an absolute component of velocity, which is the velocity component, which one would see if you are let us saying observing a compressor from outside the compressor itself that is from a inertial frame of reference.

The other velocity, the relative component of velocity is one, if which would which one would see, if your actually standing on the blade, if your now standing on the compressor blade and observe the flow; you would see the flow coming in at a different velocity, because the blade itself is moving at a certain velocity. So, that is known as the relative component of velocity, in the relative frame of reference. So, what we will do is that we will represent the compressor, the velocities in terms of water known as velocity triangles, because you now, know that there are two distinct velocity components: the absolute velocity as well as the relative velocity; and you also have the rotation of the blade itself. So, there are three distinct velocity components, now the absolute component the relative component and the blade speed. So, these three velocity components made to be put together and analyzed and that is done using what is known as a velocity triangle. So, let us take a look at what we mean by a velocity triangle.

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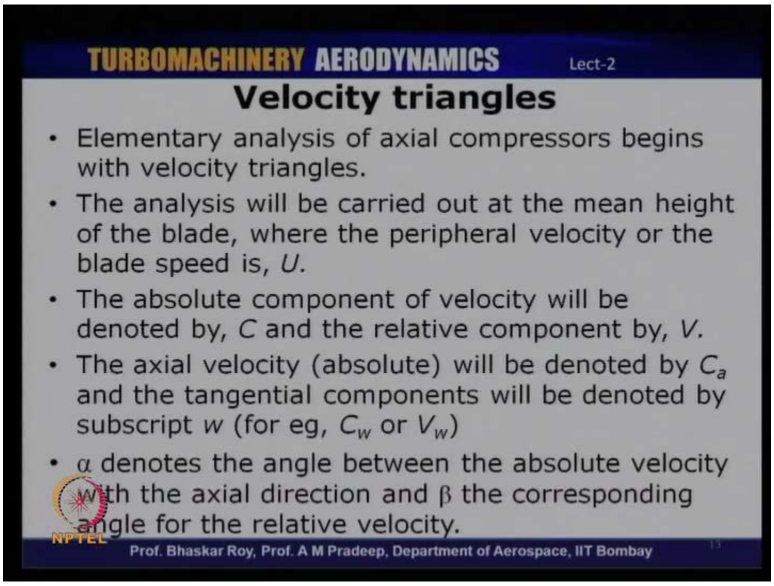

So, we begin the analysis of axial compressor in an elementary sense, using what are known as velocity triangles. So this analysis is carried out or usually at the mean blade height where the peripheral velocity of the blade speed is U, and what we do is that we will represent by the blade speed by U, the absolute component of velocity will be represented by C, and the relative component will be represented by V and so, the axial velocity, the absolute velocity in the axial direction will be represented by C subscript a, where a represents axial, and C represents absolute velocity, tangential component will be denoted by subscript w, w stands for world. So, absolute velocity in the world direction or tangential direction will be C w, relative component of that is V w; we will denote alpha as the angle between the absolute velocity and the axial direction, and beta will be the velocity or the angle between the axial direction and the relative velocity. So, alpha is the angle which is the angle between absolute component of velocity and the axial direction; beta is the angle between the relative component of velocity and the axial direction.

So, these are the notations that you need to keep in mind; C is for absolute velocity, V is for relative velocity and subscript a is for axial, w is for tangential or world and what we will see later on is subscript r, which is for radial component, at the moment we will not worry about radial component, because we are doing a simple two-dimensional analysis; alpha represents the absolute angle, angle between the absolute velocity and the axial direction; and beta represents the angle between the relative component and the axial direction. So, with these notations in mind, let us now look at how we can construct a velocity triangle for a rotor?

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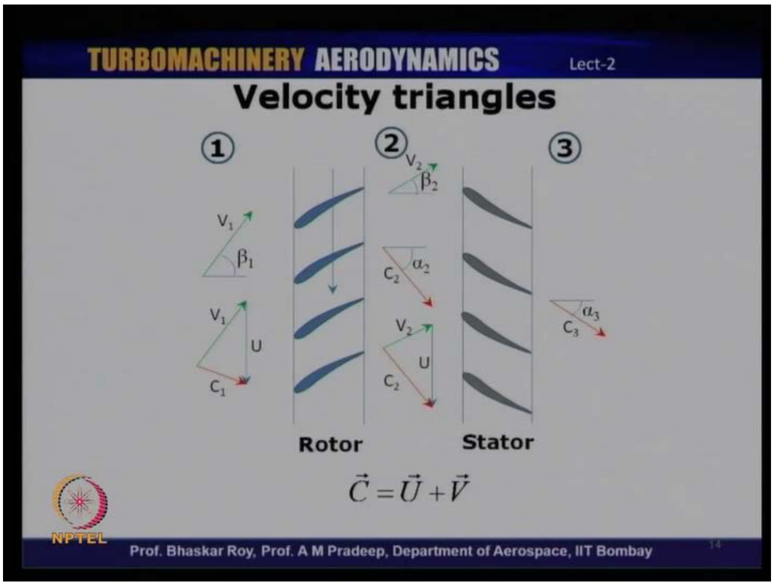

so let us look at a typical rotor and stator combination 1 stage, 1 represents for the station at the rotor inlet, and the 2 represents the station at the rotor exit, and 3 is which is also the stator inlet, 3 represents the stator exit which also happens to be the 2nd stage rotor inlet. So, these are three different stations that we are looking at 1 for rotor inlet, 2 is for rotor exit or stator inlet, 3 is for stator exit, which will be the rotor inlet for the next stage; and you can see the rotors and stators the way they have been arranged; now this is a compressor blade, so compressor blade will basically rotate in this particular direction; this is the direction of rotation of the compression blade or rotor, because it is doing work on the flow, unlike a turbine blade which you will see later, the direction of rotation the other were on because of flow does work on the rotor, here in a compressor blade work is done on the flow and therefore, this is the direction of rotation of the rotor.

Now, let us look at the velocity components one by one. So, this represents the green line arrow which have shown here is the vector representation of the relative component of velocity, at the inlet of the rotor that is V 1; now this is at an angle of beta 1 at the rotor inlet; now how does beta 1 come, beta 1 is because this is the angle which the relative component makes with the axial direction; now vectorially, we know that the difference between the relative components the absolute component is primarily because of its basically, because of the blades speed U. So, vectorially, the absolute velocity C should be equal U plus V that is blade speed plus the relative velocity; therefore, we have vectorially, some of the two that is C which is the absolute velocity should be equal to U plus W; U is the in this direction because the rotor is rotating in this direction. So, U is given by this direction, V 1 is basically the velocity which is at a tangent to the leading edge of the blade chamber.

So, at the blade chamber angle, if you draw a tangent at the leading edge that is that basically gives us the direction of relative velocity. So, if you add up all the three vectorially, the direction of the absolute velocity C 1 is indicated by the red arrow here. So, this shows us the velocity triangle at the inlet of the rotor, and now let us look at what happens as the flow exceeds the rotor, the flow will exit the rotor, the relative component of flow will exit the rotor at a in a direction, which is tangential to the trailing edge of the blade, and therefore we have V 2, which is the absolute relative velocity at the trailing edge of the rotor, leaving the rotor at an angle of beta 2.

And similarly, we can now construct the velocity triangle at the trailing edge of the rotor at the exit of the rotor, C 2 is leaving at an angle of alpha 2, alpha 2 is the angle between the absolute velocity C 2, and the axial direction; and the complete velocity triangle at the exit is given by this, that is C 2 is equal to U plus V 2, now remember that we are doing this for one particular radial location, usually the mid span; and therefore, there is no variation of U, the blade speed remains the same between the inlet and the exit of the rotor.

Across the stator, obviously there is no relative component of velocity, because they are stator blades are stationery and so, C 2 is the absolute velocity, which enters the stator and it leaves the stator with the velocity of C 3 at an angle of alpha 3. So, this completes the velocity triangle for this stage that we are discussing which is a combination of rotor, set of rotor blades and a set of stator blades; we will now look at the velocity triangles that we have just seen in little more detail, we will also look at the other components of velocity, which are involved like the axial velocity and the world velocity of the tangential velocities.

So, if we put together both these velocity triangles, which we have seen; one is at the rotor inlet and the other is at the rotor exit, we will get a combination of velocity triangles and you have seen that at the rotor inlet and rotor exit, the velocity component which is common to both of them is the blade speed that is U.

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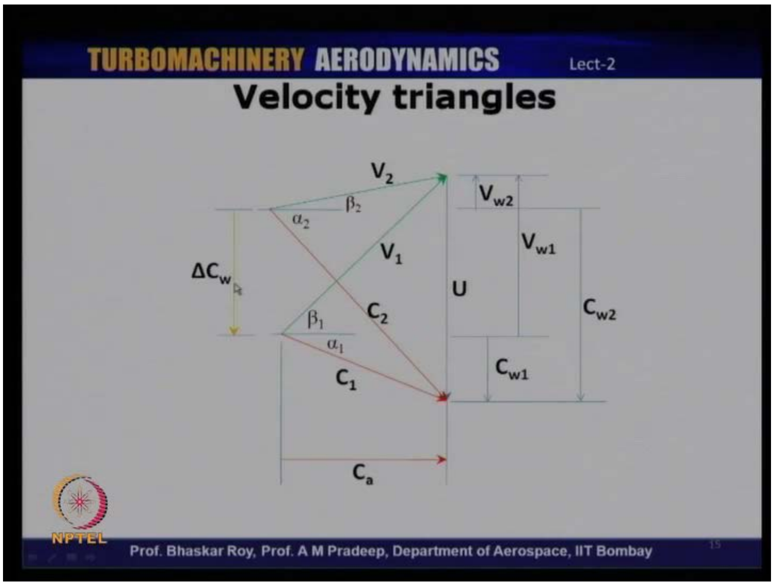

So, if we combine both these velocity triangles, what we see here is the, this velocity triangle which I am now indicating, which constitutes, which is constituted of C 1, the absolute velocity at rotor inlet, V 1 which is at relative velocity at the rotor inlet and U that is the velocity triangle at the inlet of the rotor, the corresponding angles are alpha 1 for the absolute velocity, beta 1 which is for the relative velocity.

At the trailing edge of the rotor we have C 2 and V 2, U remains the same. So, we overlap both these velocity triangles one over the other. So, we have C 2 and V 2, alpha 2 is the absolute angle at the rotor exit, and beta 2 is the angle which there relative velocity V 2 makes with the axial direction. So, both these velocities put together is what is shown in this sketch; let us also look at the other velocity components, the axial component of the absolute velocity is is indicated by C subscript a, which is also known as the axial velocity; and correspondingly we have the tangential velocities that is the component of these velocities in the tangential direction or in the direction of U, the component of C 1 in the tangential direction is given by C w 1, the component of C 2 at in the tangential direction is C w 2, similarly we also have V w 1 and V w 2.

So, the difference between C w 2 and C w 1 is what is represent here, and indicated as delta C w; this is the net change in tangential velocity across a rotor. So, as we will see very soon that this component of velocity will come up in our power calculations, what is the amount of power required to drive a compressor rotor, will primarily depend upon the change, net change in the tangential velocity. So, delta C w will tell us will give us an indication about how much is the power required to drive such a compressor this particular compressor rotor.

So, let me just quickly recap what we discussed about the velocity triangle, because we are going to use velocity triangles throughout this course, not just for compressors we will also use it for the other components like centrifugal compressors and turbines and so on. So, it is very important that we understand clearly, how a velocity triangle is constructed. So, velocity triangle as I mentioned, basically consist of three components of velocities, the blade speed that or the peripheral velocity as you might read in some books, which is indicated by or denoted by symbol U, then we have the absolute component of velocity, which is denoted by C, and the relative component of velocity which is indicated by V. So vectorially, C is equal to U plus W; because the difference between the relative velocity and absolute velocity is because of the rotation of the blade itself, and that is why you have two distinct velocity components: one in the absolute frame of reference and the other in a relative frame of reference and so, C vectorially is equal to V plus U, and that forms a basis for construction of the velocity triangles; and the direction of U obviously, comes from the fact that it is a compressor blade, and so, that determines the direction of U, and once the direction of U is known, the inlet angle of the rotor which is given by beta 1 is determined, because that is the angle at which the relative component of flow is going to enter the blade that is tangentially at the leading edge of the blade and. So, once that is fixed, you have the rotor inlet velocity, relative velocity, and then the the blade speed, and both of them put together gives us the absolute velocity as well.

So, from this concept that you have, we can also construct the velocity triangle at the trailing edge of the rotor, and at the across the stator, as we know there is no relative component so, it is just a absolute flow, which is absolute velocity, which decelerate; now the other important thing that you need to notice is that what happens to these velocity components as they move from the rotor to the stator.

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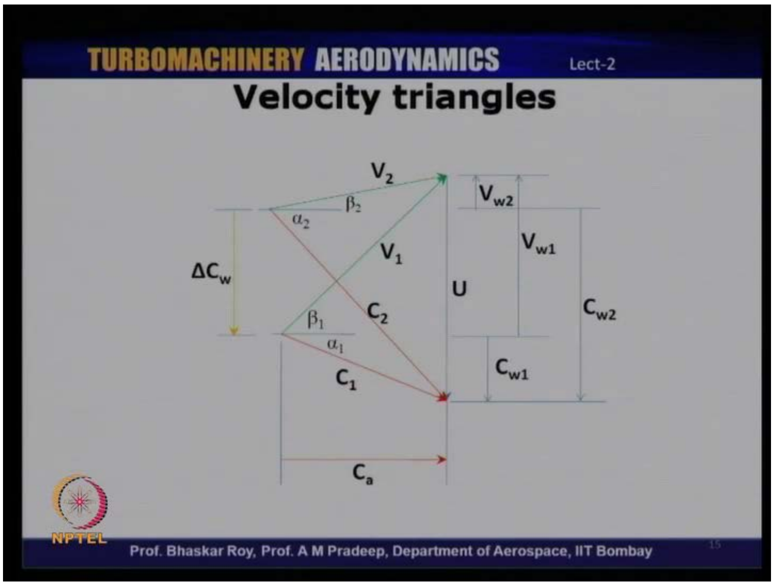

So, if we go back to the velocity triangle, which I had shown the combination of the two; what you see is that in a rotor there is a decrease in the absolutes velocities C 1 is the absolute velocity at the inlet, there is an increase in absolute velocity are there, the exit of the rotor, you can see that C 2, which is basically the absolute velocity leaving the rotor is higher is greater than C 1; on the other hand if you look at the relative velocities, V 1 is the relative velocity at the inlet, and V 2 is the relative velocity at outlet.

So, you can see that V 2 is less than V 1, and therefore the relative frame of reference, there is a decrease in velocity from V 1 to V 2, and that constitutes to diffusion taking place in the rotor, and in the stator as you have already seen, C 3 which is the stator exit absolute velocity is indeed less than C 2, and therefore there is anyway deceleration taking place in the stator as well. So, the diffusion process as we have seen even before this, is not similarly is something which takes place both in the rotor as well as in the stator, and even thermodynamically, we have seen how the diffusion takes place or compression takes place in a in a compressor across a rotor and a stator; in a rotor, you add energy to the flow, which is why it leads to increase in the stagnation temperature and stagnation pressure; in a stator obviously, there is no energy addition and so there is no increase or no change in stagnation temperature, but usually because of losses there could be some change in stagnation pressures across a stator.

So, velocity triangle is the starting point for any simplified design and optimization analysis, and before one takes up a very detailed analysis and detail design of compressor stage, it is the velocity triangle from which the entire design exercise begins, and I have also mentioned about the significance of the simplified two-dimensional analysis in the design cycle, the fact that a simplified design gives us a very quick design turn around and optimization can be carried out much quickly, if your restricting our designing initially to a simplified two-dimensional design, before taking it to a detailed component design, which is much more complicated and time consuming. So, the significance of simplified two-dimensional analysis lies in the fact that it is required for us to estimate the work requirements of the compressor gives us some idea of the efficiency that the compressor is going to give us, and the fact that its much simpler to carry out as well as the design whole design cycle takes much shorter time, and if there are optimization techniques to be taken up before the detail design is taken over a simple two-dimensional aerothermodynamics analysis gives us a much better analysis at the stage. Now, let us look at what happens as the flow passes from a rotor through a stator what happens to the properties of the flow as it moves from a rotor across to a stator.

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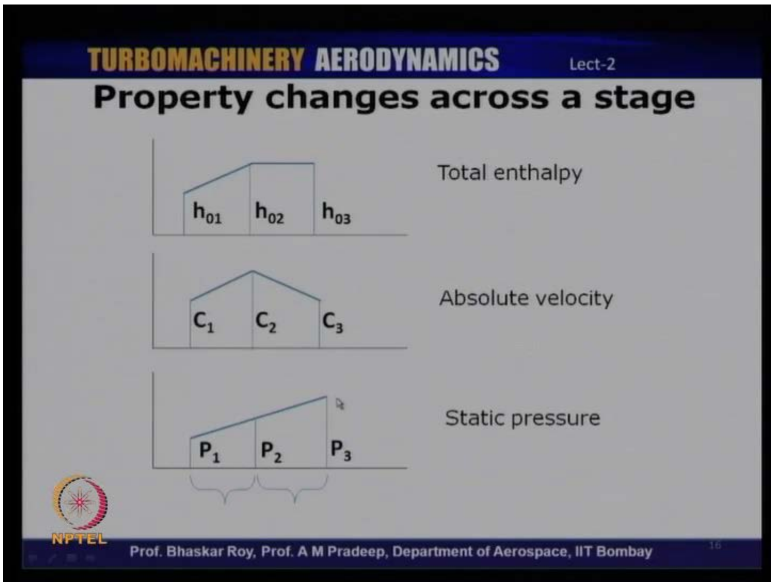

Now I have plotted here three different properties: one is the enthalpy, the other is the absolute velocity and the third is a static pressure; now these three distinction lines that are shown here that is state 1 here represents the rotor inlet and state 2 represents rotor exit or stator inlet, and state 3 here represents the stator exit.

So, as the flow moves from the rotor inlet to the exit, there is a change in the enthalpy, the stagnation enthalpy are the total enthalpy changes there is an increase in stagnation enthalpy as the flow proceeds from a across the rotor, this is because of the fact that there is energy added in the rotor and that leads to an increase in stagnation enthalpy; in the stator on the other hand, there is no change in stagnation enthalpy, because there is no energy added or removed in the stator; on the other hand if you look at the absolute velocity, absolute velocity C 1 and the inlet of the rotor, and we have seen in the velocity triangle that there is an increase in absolute velocity as it passes through the rotor, and therefore, C 2 is greater than C 1, absolute velocity at the rotor exit is greater than the absolute velocity at the rotor inlet, in the stator there is deceleration taking place that is C 3 is now less than C 2. So, there is a decrease in absolute velocity as it passes through the stator.

Static pressure increases all through that is in the rotor as well as in the stator, and we have seen this in the T-s diagram, the temperature entropy diagram that I had shown earlier on that there is an increase in static pressure taking place in the rotor as well as the stator. So, this is how the properties changes as the flow passes from the rotor across as a flow moves across the rotor and across the stator. So, there is a change in all these properties, stagnation enthalpy, absolute velocity, stagnation pressure. In fact, I have not have not shown that here stagnation pressure increases in the rotor, in the stator in an ideal case it remains constant, but in actual compressor one would have decrease in stagnation pressure in the stator, because of losses taken place in the stator.

So, this is just to demonstrate, how the properties vary as it moves through a rotor and a stator; now let me quickly recap our discussion in today's lecture, we started our discussion today with some amount of discussion on the significance of simplified aerothermodynamics analysis, and then we subsequently we discussed about how we can represent a compression process in a thermodynamic sense in pressure volume as well as temperature entropy plots, and we have seen the compression can be other diabetic or isothermal or it could be polytrophic, and then we looked at the compression process taking place in a single single stage compressor across a rotor and then a stator; and then we looked at the compression process that takes place in a a multi stage compressor that is across multiple rotors and stators, how we can analyze a the compression process in a thermodynamic sense, after that we spend some time on discussion about how we can represent the velocity components across the rotor and the stator in terms of velocity triangles; and velocity triangles as I mentioned forms the the starting point of design exercise, where one would like to construct velocity triangles across the rotor and stator, and see how the properties vary. So, these were some of the topics that we had discussed in today's lecture, we will continue with some of these topics in the next lecture as well where we will discuss, basically about work and compression taking place in a compressor and subsequently, we will begin with some two-dimensional analysis and performance parameters which are used in analysis of axial compressors, we will also spend some time on discussion of what are known as cascades, which are basically testing methods used for simplified two-dimensional analysis. So, we will discuss some of these topics in the next lecture which will be lecture number 3.