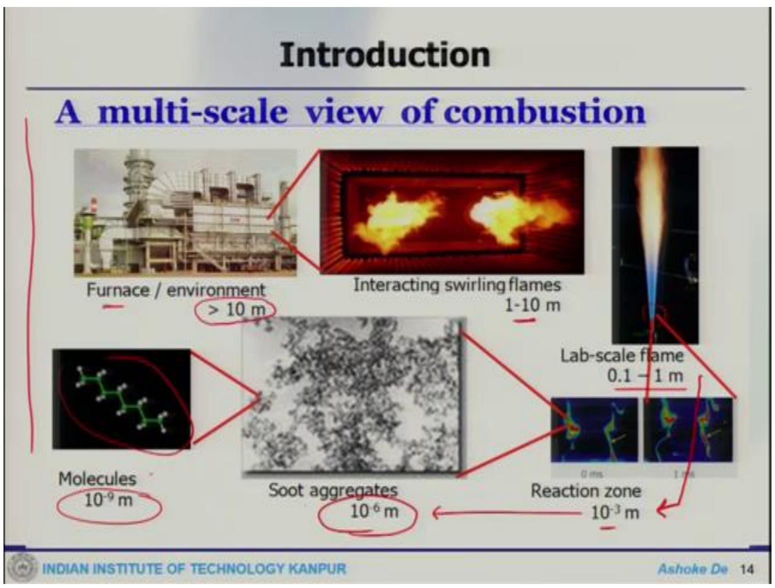
Turbulent Combustion: Theory and Modeling

Prof. Ashok De
Department of Aerospace Engineering
Indian Institute of Technology-Kanpur

Lecture-2
Introduction to Combustion (Contd..)

Welcome back so will continue the discussion where we stopped in the last class is the optimisation of this gas turbine unit.

(Refer Slide Time: 00:28)



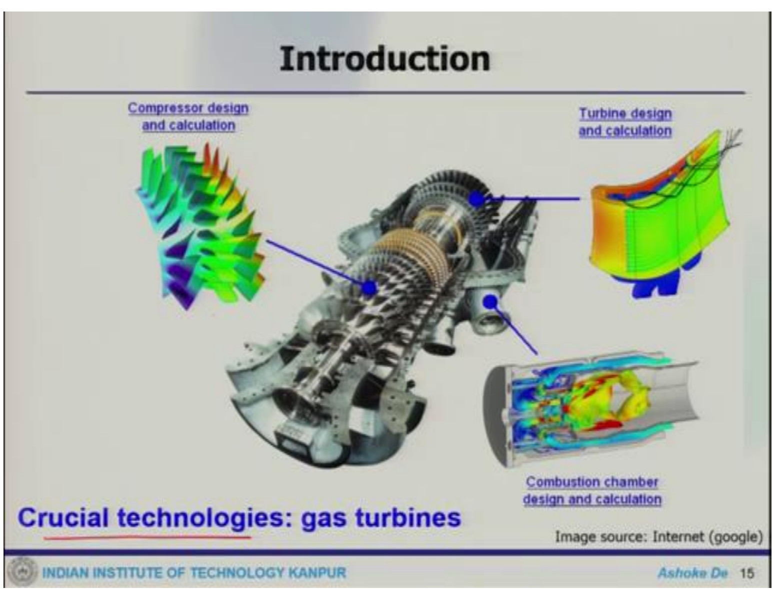
Now we will see the different side of a combustion now because one of the key component is as we said is the combustion one can see a multi scale view of combustion which will give you an idea that ah starting from this is our label where you see the furnace application in an industry that’s in one scale the large-scale application of combustion with the boiler and all these furnaces there used. From there the; why we say the multi scale because the here scale is always higher than 10 metre and also.

But when you look at in the some or other aspect where the swirling flames they are interacting so this is scale for its change of some scale between this application to this application. Now you move to the laboratory level scale that mean these are some of these flames which are there the scale is 0.121 metre, so immediately there is a change of order of magnitude and when you look at this particular zone zoomed in this is how you look at the reaction zone and we call it a reaction zone.

As we go on having our discussion on different kind of flames and such like that we will see how this reaction zones and their characteristics and all these but one at this moment and see that the ah scale of reaction zone is so there is a from this to this, there is a change of quite a bit of order. Now within the reaction zone you can have this kind of small particles which are called soot particles and I mean essentially when you look at the applications of that this is what the black particles which comes out of your automobiles from industrial Chimneys and other applications where the black smoke kind of things comes out because of your combusting unit.

And these soot particles their length is of this; so there is huge change in order of the length scale. So, and finally when we come down to the molecular level that is the scale where actually reactions and other things take place. So, you call it everything together you can see starting from a molecular level up to this furnace kind of application there is a different kind of range which are associated. It depends on the particular application that what kind of range one has to delete it but if you couple everything together you can think about this is a really a multi-scale Multiphysics kind of problem.

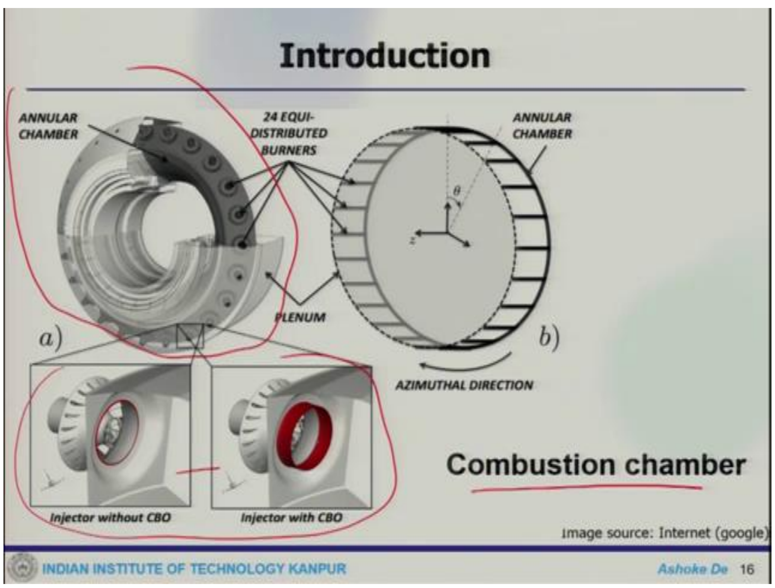
(Refer Slide Time: 03:32)



So, now again coming back to some of the example of the gas turbine unit so this is a gas turbine unit's cut section of a gas turbine. So, why we keep on coming back to this gas turbine unit because this is one of the crucial technologies. There are so many components so many units they are connected together and one can imagine that engine is the only concerned element that actually allow that big airplane to fly.

So, you can see these are the compressor, these are the turbine components and here you sitting the combustor. So this is also sort of also associated with multi scale phenomena because when the flow past the compressor this is the different scale and enters to the combustion chamber with the different scale where the reaction goes on to reactions taking place at a different scale fuel is injected if it is a liquid fuel in that brings in different kind of combustion technologies and the scales evaporation and all this thing and finally it goes out to the turbine and all this thing.

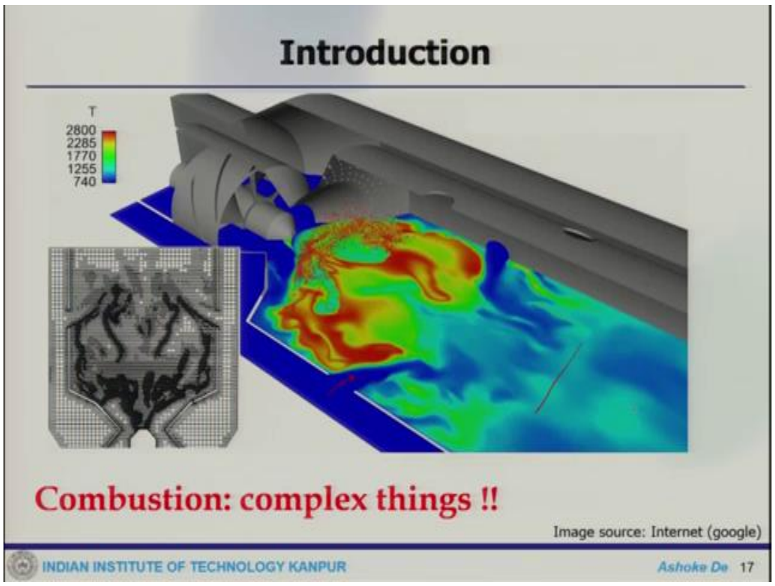
(Refer Slide Time: 04:52)



So, technology-wise this is quite crucial now when you come to an individual component of combustion chamber one can see these are the some schematic of the combustion chambers, this is a combustion chamber with a annular distributed burner so essentially along this of burner are situated one can see this and these are annular sections and each burner has injector with this kind of configuration.

So, each of these individual burners one can see because these are the cut section which are shown for individual burner and one can see that they are so complicated. I mean this is sort of a global picture more or less like a micro level picture in that sense. Because individual burners which are located around this peripheral there are so many and that is why you get so much of power. But at the same time when you look at that individual component they are so complex.

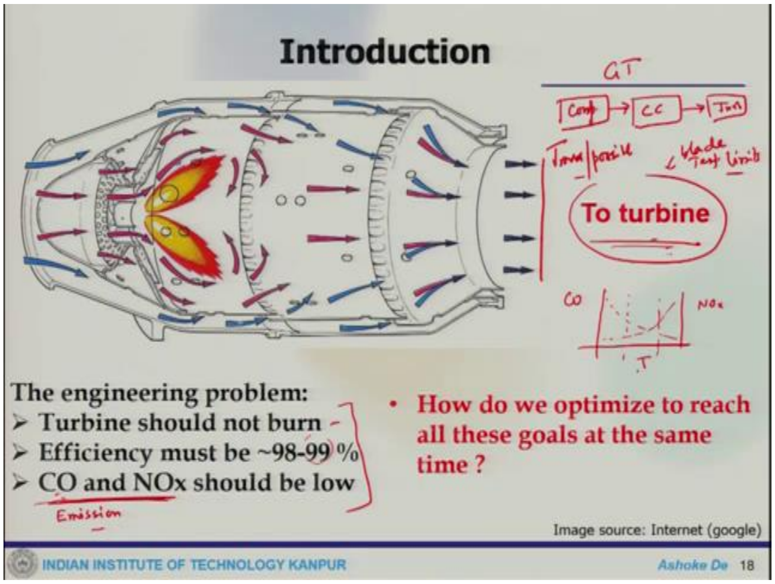
(Refer Slide Time: 06:06)



Now this one will tell can you or give you an idea about the kind of complications of this is again an image which is adapted from the internet that individual cut section of a gas turbine combustor where you see these are the delve in through which the; here comes in and it get the swirling energy and there the liquids and this particle shows that the liquid fuel which is injected and a kind of reactions and then you have a secondary tertiary injection.

These are the holes which are used there are multiple purposes of using those holes because it gives you an advantage of mixing also so that the temperature distribution at the end becomes quite important so that the pattern factor reduces which is one of the desired aspect. At the same time, it allows to cool the surfaces of the combustor wall surfaces and hardly because of this unit of temperature distribution, your emission also reduces. So, there are multiple aspect but what is important here? So if you look at this combustion process, there are so many complex things which are actually taking place.

(Refer Slide Time: 07:25)



Now what are the problems seen so you can see this is one of the; this kind of combustor unit where ever primary air comes in, then you inject the fuel with the combustion takes place this around the peripheral you have all secondary tertiary holes so there are different impact of this holes through which the fuel air are injected and finally this combustion product on the hot product goes to turbine. Now what is important here because this particular component, so before and for a GT unit you have a compressor, compressor fit to combustion chamber, combustion chamber fit to turbine. So, you can pump in any amount of; so whole idea of this combustion is that you convert your chemical energy to the thermal energy so one may wish to pump in more and more air and fuel so that you have more combustion and you get more energy but there are restriction to that because it is not only that your combustor material of the combustor liner they have to withstand those temperature at the same time this hot product which are going to the turbine.

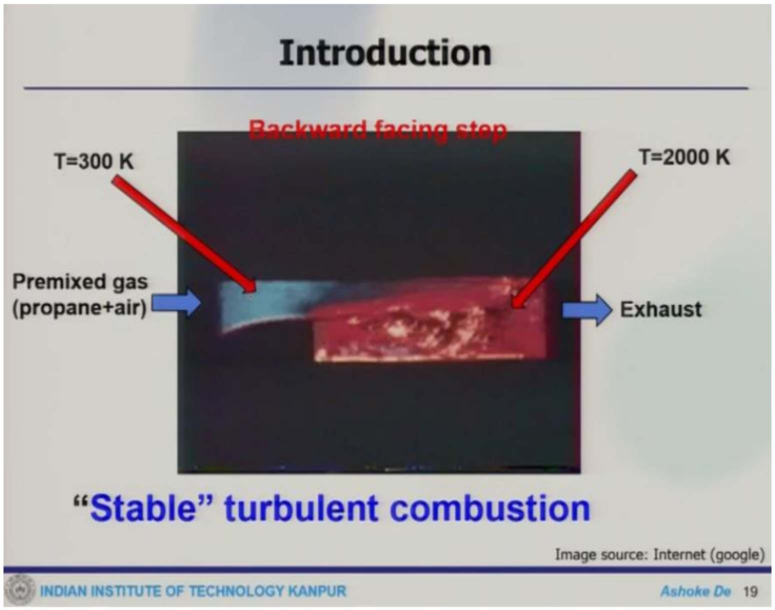
So, the turbine blade has certain limit. So, blade temperature limits the design because the blade has a particular material and the material has certain limit to withstand the temperature. Essentially for GT unit all these designs come from the downstream component like turbine. Turbine material or the blade material actually dictate what could be the possible maximum temperature so that T_{max} which is possible. So, this possible temperature will be kind of maintained to the combustor, so this will dictate what could be the hot product that is in entering there. So, that means it is not that I would have a combustor and I can burn as much as fuel and I can produce energy with that has some restriction and the restriction in the terms that determine would not be able to withstand that so one may look at what are the engineering problems here.

So, if I am a designer my whole point should be turbine should not burn that means turbine blade should not burn so that is one of important point then at the same time because this will dictate what could be the possible maximum temperature or at the same time I would like to have the efficiency. Typically any gas turbine combustor the efficiency lies around roughly 99%. So, there is not too much of loss. The combustor is one of the component in a GT unit where you have quite efficient system. And then third is that emission so this should be low so that means my CO and NO_x should be low. So, that means I am trying to again optimise the whole system I do not want to increase my temperature to a limit which will lead to a catastrophic failure of the turbine element at the same time I want my efficiency to be close to 100% if not still remain 99% efficient and the emission which is another stringent norm that one has to follow that means the emission norms should be fulfilled.

So, that give the important question. How do you optimise to reach all these goals at the same time? That means there are certain things which are counter intuitive. Because if you go to reduce one of these element other may go up or other may go down if you; so it is an again trade off especially in terms of emission because this guys are also dependent on temperature. Too high temperature the NO_x will go up and the CO come down. So, it just like an; if one plot the temperature axis and NO_x and CO to high temperature this will go up and too high temperature this will come down but if you go too low temperatures CO will go up and NO_x will be low. So, that means even in the emission product there are different characteristics. So it is in trade off of one need to operating system in a bandwidth limit of temperature.

So, you sort of compromise on this emission and at the same time this compromise with hub impact on the turbine blade. But at the same time if you operate between certain limits, your efficiency may not be that high.

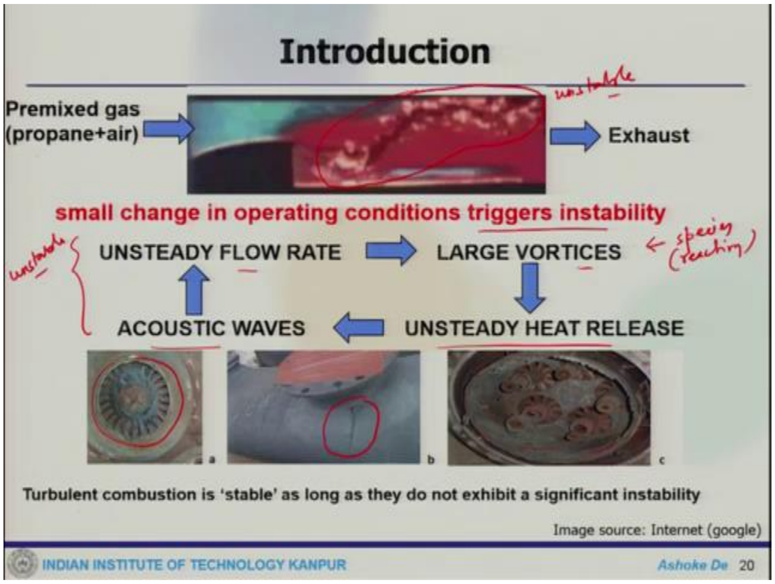
(Refer Slide Time: 12:47)



So, we talked about different kind of combustion their application the impact on the downstream component of different units and all these; there is a simple example of backward facing step where you have propane and air is a premix gas which is injected at temperature like this and this is the combustion product and this goes to basically exit or the exhaust. What we can from the image one can see this combustion adjustable I mean obviously this is a turbulent combustion. This is no more very calm nice looking combustion like your candle burning it is a stable combustion. Does that means we can have unstable combustion? Yes it do. And even in this particular case as long as you are sending this mixture which is burning here, so you get some sort of stable combustion. So, mixture is coming in it keeps on burning you get everything stable. You changed some of the parameter at the, hasten, you modulate the; this upcoming mixture or you modulate the fuel flow rate or air flow rate of these things.

So, any of these things small change in the operating condition it would lead to an unstable condition and rather one can say that it triggered the instability and you can see there is a huge difference in the flame structure. So, previously it was a nice stable structure now you see this is quite unstable structure and how it happened? It happens because somebody might have to scale the optimum condition. So, one has to understand that combustion is nothing but your some reactants and oxidizer these are multispecies systems which are converted due to underline fluid mechanism. So there starting thing is in the fluid mechanical behaviour things would lead to this kind of situation and what happened there that you have some unsteady flow rate so that means as I said it say dynamical system coupled with so many different scale, different phenomena.

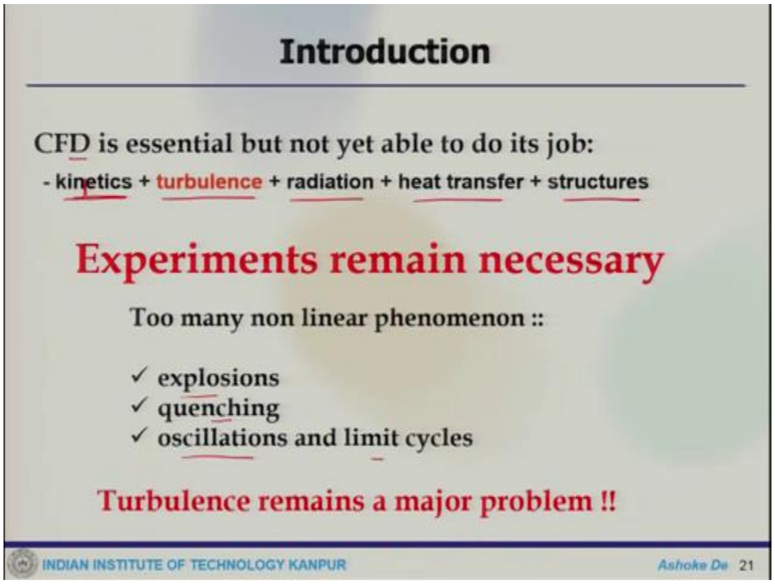
(Refer Slide Time: 14:03)



Not only fluid mechanics, fluid mechanics reactions, frictions, mixing everything is there, so there is unsteady flow rate and the unsteady flow rate which will have large vertices. So, when you have large vertices that means any turbulent flow will have large vertices and what you will see later on when we talk about the turbulence how this large vertices actually behave their characteristics scales all sorts of different things. And that will lead to some sort of unsteady heat release that means when you talk about this vertices they are actually carrying those species or rather reacting species and reactive species they are also exposed to the underline fluid dynamical behaviour and that will lead to unsteady heat release which will generate some sort of acoustics waves. So, once that happened this gain is going to couple it back.

So, that makes the whole system literally unstable and once you have this unstable system so you may have some consequence. So these are some of the images of those things for you can see there is a big track on the combustor wall see what happens to the swelled burners some damage to the dumb plane and the combustor walls. So, this kind of instabilities has huge impact on the operating conditions as well as on the materials point of view. So, one can think about the turbulent combustion is a stable one as long as they do not exhibit any significant instability.

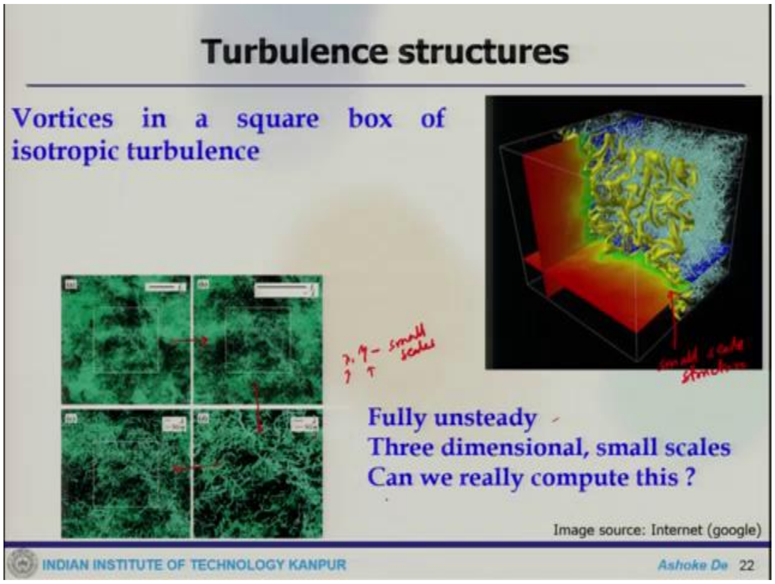
(Refer Slide Time: 17:25)



So, what is important? Important is that then one has to look at things through safety which is quite essential but not able to do its job because of so many things. You have kinetics which is important for any combustion which is connected with turbulence then depending on the applications you have radiative effect, you have huge heat transfer, structural impact. So, it is not like that experiments are always expensive and something like that but sometimes it is also quite difficult for problem like turbulent combustion.

You have so many connected flow physics and so still one can think about experiment is really necessary because there are so many nonlinear phenomena that take place in a combustion. It could have an explosion or when the combustion is taking place there could be local quenching that could be another possibility or there are oscillations and limit cycles and all the issues the backbone of that is the turbulent. This is what a major problem remains so that means if you see things happening when you talk about the turbulent combustion and the combustion itself is complicated. On top of that, when you are kind of dealing with the turbulent system that creates another level of problem of that remains in huge problem.

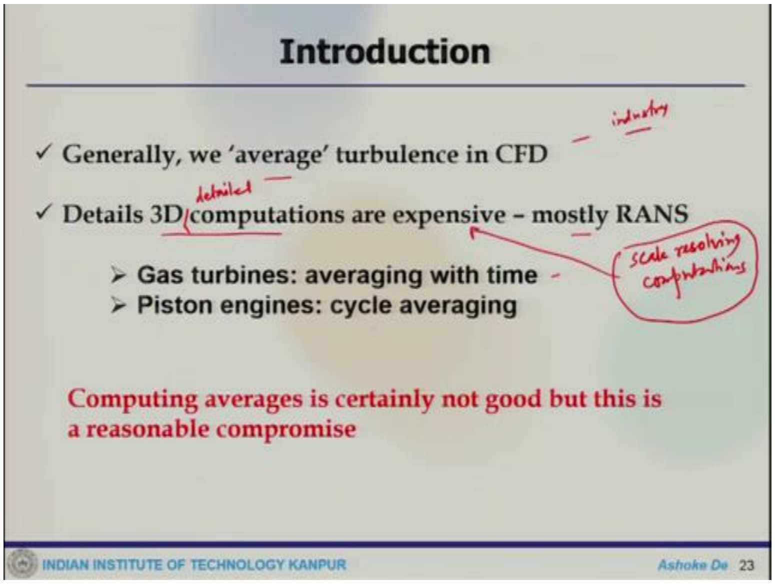
(Refer Slide Time: 19:20)



Just give you a glimpse of what turbulent flow field looks like though will discuss this things in details as we move along with our lectures. This is in a box isotropic turbulence that means it is sort of a homogeneous. If you see the small scale vertical structure, these are small scale structure, vertical structure. And these kind of structure along with the large scale structure they do participate reactive system. So what it does one can see different images this is an acoustics view and if you zoom in you can see different kind of view.

You zoom in more so essentially in a turbulent structure idea is that as you keep on zooming in you look to see a different kind of structure at different scales and that is what it is a large scale is an Eta Lambda these are some sort of scales which are used in turbulence and will discuss about this things but these are the; when you go to Lambda or Eta these are the limits of small scale and defined by different scientist. This is Taylor length scale, this is called Kolmogrov length scale and idea is that as this is an isotropic box and if you zoom-in this picture you can see it is quite unsteady in nature this is truly three dimensional and they do have lot of small scale structures and all this so I did that, all the question is that can we really compute this? But it requires sophisticated modelling technique so one can handle this kind of situation.

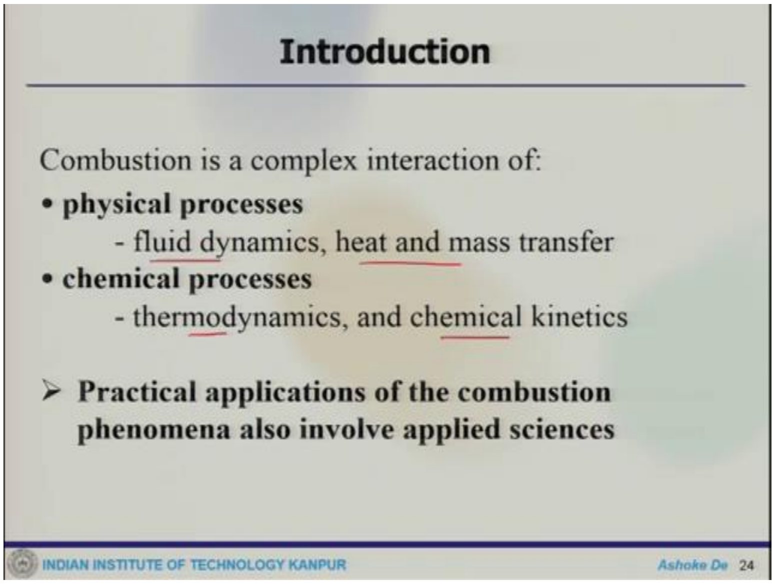
(Refer Slide Time: 21:26)



So, what we do usually and what are the sort of impact of doing that and once you do that usually what we do to model the turbulence it is a very much white common in industry because there we used to get a solution in quick time so there is turbulence. But as you have seen the turbulence itself is truly unsteady and three dimensional is nature it requires really 3D computation or 3D detailed computation. So, which can resolve all the scales.

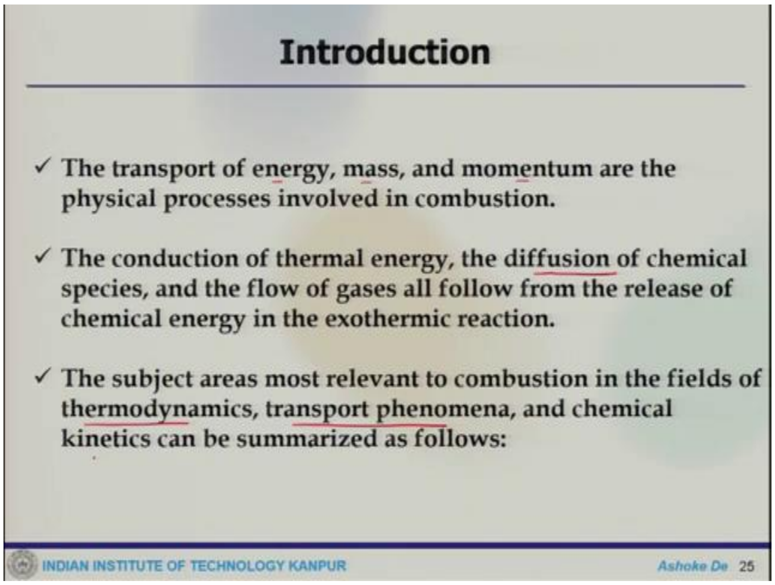
So, or one can think about scale resolving computation but if you talk about scale resolving computation that is quite expensive. So, what people do sometimes in academia sometime and mostly in industries they use mostly RANS scale and you get the solution in quick turnaround time so that is what to do the averaging and what kind of averaging you do on a couple of them if you look at the gas turbine averaging with time because the unsteady flow. And when you go to piston engine you go by the cycle how many cycles and the do the cycles adding. But if one has to answer this question is the averaging is a good idea obviously not but this has some reasonable compromise because by doing this one can get solution in quick time.

(Refer Slide Time: 23:18)



So, what if you put things together combustion is a complex interaction of so many different process there are physical processes which are like fluid dynamics issues heat mass transfer issues then it is associated with chemical processes like your chemical kinetics, thermodynamics conversion of the chemical energy to thermal energy and not only that any real life applications of this combustion they also involve lot of Applied Sciences.

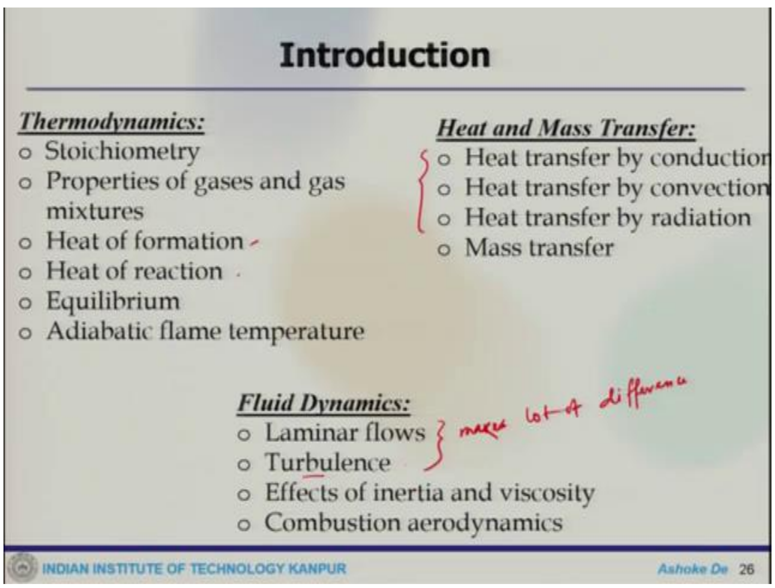
(Refer Slide Time: 24:01)



So, if one has to look at it in a combustion process what it happened so it can be governed by few fundamental governing laws like energy, mass, momentum so these are the physical processes which are involved in combustion and they are transported .so mass, momentum, energy. So, top of that you have some conduction of thermal energy, diffusion of the chemical species because without that your reaction cannot take place.

So, because of that interaction of the different species at the molecular level that would allow to reaction to take place and evolve and then flow of the gases all follow from the release of chemical energy into the exothermic reaction. So, the things which are more are mostly relevant in combustion one is very, very important is the thermodynamics, transport phenomena, transport phenomena means your momentum transport, species transport, mass transport, kinetics and some of these one can summarise.

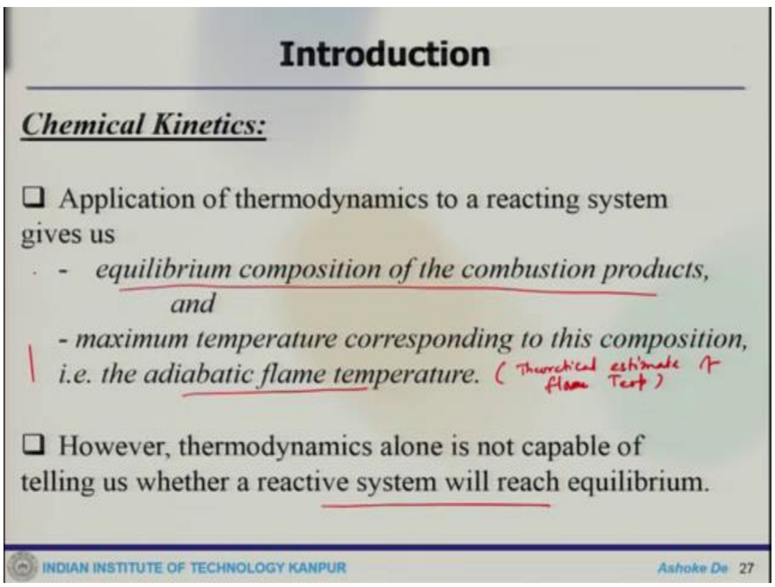
(Refer Slide Time: 25:14)



So, if you first look at how the Thermodynamics is going to act to that you define different things like equilibrium, heat of formation, heat of reaction, properties of gases, stoichiometric, flame temperature these are the things one would be able to estimate to the thermodynamical analysis. Now, once you bring in heat and mass transfer so your heat transfer due to convection, conduction, radiation any of the modes. And the depending on the problem you deal with you have this heat transfer and that to be taken into account and then mass transfer obviously because you were transferred in different species which are involved in this particular process and they actually do take part in this kind of heat and mass transfer. And finally your fluid dynamic features these are also very important whether you could have a laminar flow or turbulent flow because this makes lot of difference.

Lot of difference already you have seen the glimpse of this turbulent combustion and if you think about your candle burning this is nothing but your laminar flows and laminar burning so it's too calm and smooth there is no apparently issues which should be immediately catastrophic but when you talk about turbulent reacting system that could be. Then there are inertia, viscosity all these transport properties and combustion aerodynamics.

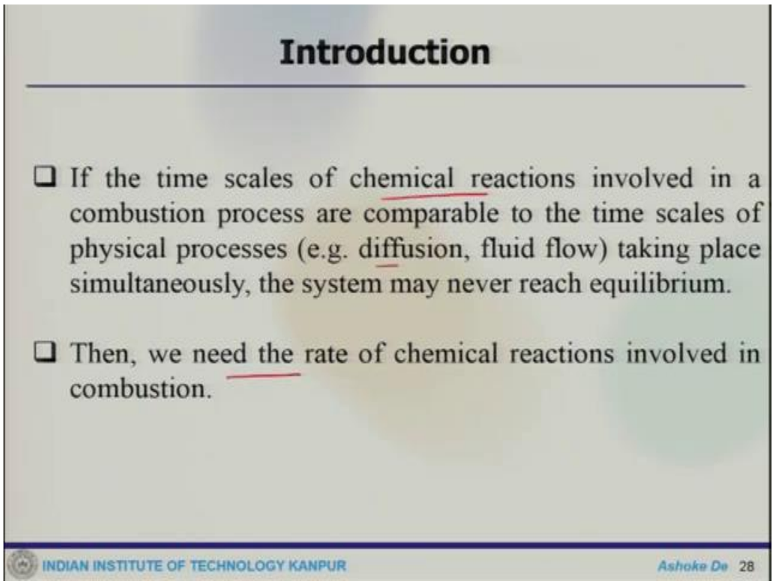
(Refer Slide Time: 27:09)



Now you come to the kinetics this is nothing but the application of thermodynamics to the reactive systems which will give you an equilibrium composition of the combustion products that means when multiple species they are reacting to each other one can estimate what would be the equilibrium compositions. So, that means it just like in collisions between different molecules and there is to a certain equilibrium.

And at the same time because of that the maximum temperature corresponding to this kind of compositions which will so called adiabatic flame temperature or rather this is a theoretical estimate of flame temperature for a given species or given reacting system or a particular fuel and the oxidizer. If you change the fuel this theoretical limit or estimate actually; so, thermodynamics talks about these things but at the same time one has to also know that thermodynamics alone is not capable of telling whether the system will reach to equilibrium or not. So, that is another issue that means thermodynamics can give you estimate of this thing limits equilibrium compositions and all this thing but it does not tell you that.

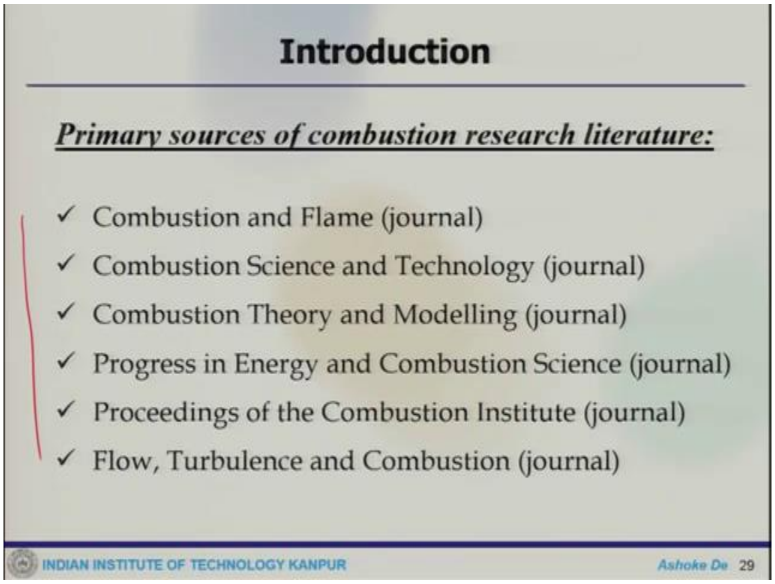
(Refer Slide Time: 28:44)



If the time scale of chemical reactions involved in the combustion process which are comparable to the time scale of the physical process that means the diffusion fluid flow taking place simultaneously. Unknown source system may never reach to equilibrium that means immediately your other aspect of the things comes into the picture like there is a convection taking place due to fluid dynamic behaviour.

And that allows to have diffusion to take place and the time scales are quite different. Now the typically in any reacting system the time scale of chemical reaction is quite different from this kind of other time scale so that is some other important issue which comes into the picture how one has to deal with this different time scale. So, one has to calculate the rate of chemical reactions which are involved in the combustion.

(Refer Slide Time: 28:40)



So some of the materials are also collected from the; these are not all but these are the primary source of combustion, so literature on may look at these because every time there is a issue out there one can see different aspects we discussed these are the sort of primary sources one can look at and then get more insight about recent advancement and then that details. So, I will stop here and take it up in the subsequent lecture, thank you.