Combustion in Air Breathing Aero Engines
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Lecture - 53
Flame Stabilization and Blow off-I

Welcome back. So, in the last few classes, we have discussed about gas turbine combustors, in particular aerospace gas turbine combustors and we have seen how the different parts are connected together like how diffuser, the combustor liner, all those things are connected and how the flow is essentially split into the primary zone, into the dilution zone etcetera which eventually determines the final temperature profile that goes into the turbine, but as such the main thing was that the temperature profile at the exit of the combustor is of very high importance and as such the maximum temperature though is useful towards, though we want to maximize the temperature because that causes increase in the cycle efficiency that is essentially limited by the material properties and the coating properties of the turbine blades as such as a result of that in the combustor, the overall fuel, actual fuel ratio divided by the stoichiometric fuel air ratio which is the equivalence ratio.

The overall equivalence ratio remains very lean 0.04 something like that and the air fuel ratio is always very high, much higher than the stoichiometric values. So, as a result there is lot of oxidizer, lot of air still left which can be utilized for further burning, but the reason why we cannot burn more fuel inside the combustor is that if you burn more fuel inside the combustor, then the temperature will approach. The stiochiometric have different temperature and that is not acceptable when the turbine blades even though there is air present, excess air present inside the gas turbine, the main gas turbine combustor you cannot utilize that because your turbine inlet temperature or the turbine entry temperature is limited by the material properties.

So, there is a lot of air. So, the question is that in cases where you need extra thrust, suppose you are using a military gas turbine, you are designing an engine gas turbine, engine for military applications, where the aircraft might need to accelerate, might need to take sharp turns, might need to climb up very rapidly. So, we need all these menu verse all this like extra vagant maneuvers needs extra thrust. So, what one can do is that one can utilize this excess air that goes out of the gas turbine engine and burnt fuel in this excess air after this excess air comes out of the turbine, all right.

So, that is what exactly the purpose of an afterburner is. So, the afterburner essentially as you see the afterburners are essentially is a long pipe which contains a ear that goes out of your turbines and you dump fuel in the air, you spray fuel in there and you essentially burn the fuel there and you generate extra thrust by accelerating the hot gases that comes out through a nozzle. So, that is what an afterburner does, but the thing is that here the flow that there are afterburner encounters comes out of the turbine. So, it is already expanded.

So, as a result on one hand, it is vitiated that it contains some amount of combustion products that comes out of the gas turbine engine and on the other hand, also the flow velocities are higher. So, one big challenge in this afterburners is flame stabilization and even more. So, because you are using this afterburners in kind of short intervals where the flame, where the aircraft can accelerate. So, the acceleration in the aircraft can also cause acceleration in the airflow inside the afterburner. So, the afterburner sees a stringent conditions in terms of limits stabilizations.

So, in this code topic, in this module what we look into is that.

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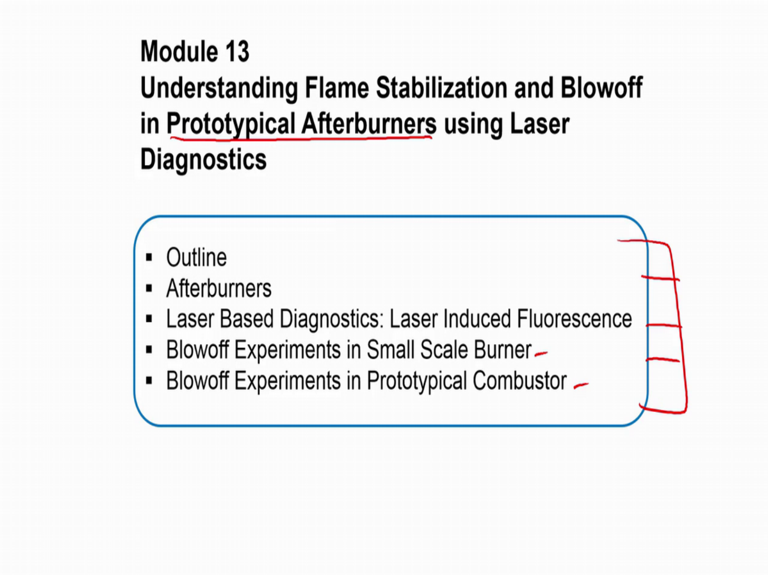

Module 13
Understanding Flame Stabilization and Blowoff in Prototypical Afterburners using Laser Diagnostics

- Outline
- Afterburners
- Laser Based Diagnostics: Laser Induced Fluorescence
- Blowoff Experiments in Small Scale Burner
- Blowoff Experiments in Prototypical Combustor

We will look into understanding flame stabilization and blow off in prototypical afterburners and using laser diagnostic. So, this module is rather unique. The next 3-4 classes that we will go through is that are unique because it does not really, it talks about many things. It essentially tries to understand the very important combustion problem that is flame stabilization and blow off in this kind of rather prototypical configuration, in a practical kind of configuration using laser based diagnostics. So, here we are going to introduce this cutting edge diagnostic techniques called laser diagnostics, in particular laser induced fluorescence and particle image velocimetry which can be utilized towards understanding some particular phenomena that happens in a practical engine.

So, this course essentially will cover many things, but I hope you will enjoy this course because this class will cover many things because on one hand we will be talking about practical system and on the other hand, we are talking about a practical problem because flame stabilization and blow off is indeed a practical problem in the afterburner and then, we will attack that problem. We will try to understand that problem using these experimentations. These are based diagnostics and we will show you that how this complex engine condition can be simplified into smaller configurations in an experiment, in a laboratory experiment and then, once we develops an understanding of that laboratory experiment, we can construct bigger facilities in which we try to understand this thing.

So, this will be like an amalgamation of different things like practical engines, afterburners, laser bell diagnostics as such and will blow off experiments in small scale burner and blow off experiments in prototypical combustor. So, we will try to cover quite a few ground here and this will be a further little bit different test than what we have done before, but also here as such in this whole course, we have never compromised on the rigor. We have always done deeper analysis in a simplified. The system we will also do that same thing that is we will try to instead of just describing that to do laser induced fluorescence, you need a laser, you need a camera etcetera. We will tell you what the principle behind laser induced fluorescence is, so that we develop this concept from a very fundamental report, ok.

So, here is the outline, ok.

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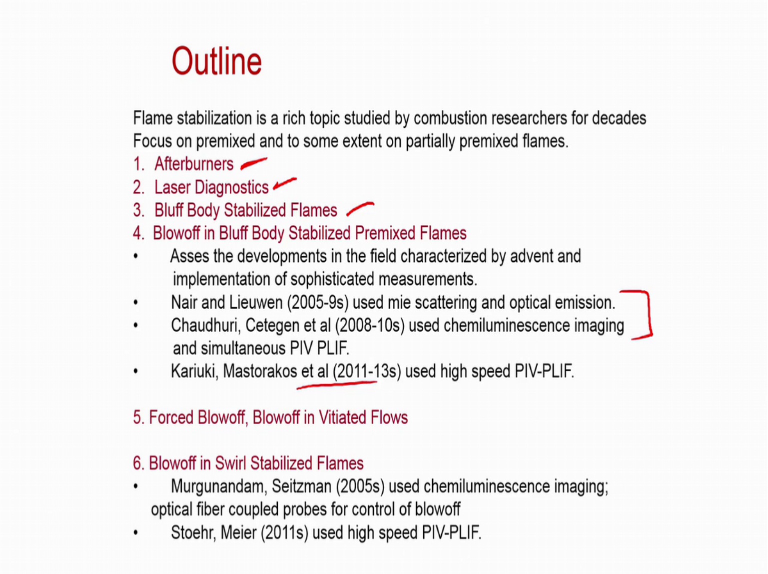

Outline

Flame stabilization is a rich topic studied by combustion researchers for decades
Focus on premixed and to some extent on partially premixed flames.

1. Afterburners
2. Laser Diagnostics
3. Bluff Body Stabilized Flames
4. Blowoff in Bluff Body Stabilized Premixed Flames

- Asses the developments in the field characterized by advent and implementation of sophisticated measurements.
- Nair and Lieuwen (2005-9s) used mie scattering and optical emission.
- Chaudhuri, Cetegen et al (2008-10s) used chemiluminescence imaging and simultaneous PIV PLIF.
- Kariuki, Mastorakos et al (2011-13s) used high speed PIV-PLIF.

5. Forced Blowoff, Blowoff in Vitiated Flows

6. Blowoff in Swirl Stabilized Flames

- Murgunandam, Seitzman (2005s) used chemiluminescence imaging; optical fiber coupled probes for control of blowoff
- Stoehr, Meier (2011s) used high speed PIV-PLIF.

So, first we will go about this flame stabilization as such which is a very rich topic and it has been studied by combustion research for decades and we will see that the flame stabilization indeed involves quite a few things. It indeed involves like understanding will involve like you have to understand how combustion happens in a practical flow that is typically we used flames essentially stabilized in sheer layers. So, on one hand we will need to understand properties of sheer layers like different kinds of vortex shedding. When you know the vortex shedding that can happen in a reacting flow, vortex shedding have that happens in a non-reacting flow and then, we will look into the properties of the flames, we will see how flames speed changes with different conditions and how flames can extinguish by stretched rates etcetera. So, it is a combination of many things and as such all this understanding of a combustion that we have developed.

So far in we will essentially feed into this topic so many things. It essentially goes into successful flame stabilization and that is the purpose of these few lectures and then, where the outline is that we will go and look into afterburners because that is the practical application that we have in mind in flame stabilization. Of course, a flame stabilization you have to understand. The flame stabilization is a very important requirement in high speed propulsion systems in ramjets and scramjets. So, those configurations might be little bit different because in a scramjet example you have two flames. You have to stabilize the flame in a supersonic flow. So, fundamentally there can be some differences, but still the understanding that developed here will go a long way in describing those phenomena as well as we will see later, ok.

So, then first we will go into afterburners and then, we will go into laser diagnostics, principles of laser based diagnostics. How do we do, what is the fundamental principle behind laser induced fluorescence and how do we do laser induced fluorescence and then, we will go in to look into bluff body stabilize flames will assess the development in the field for the last 50 years in very brief view and then, we will go into the recent works by Lieuwens group in Georgia Tech and then, we will go into our works at university of group where we will use chemiluminescence imaging and PIV and PLIF etcetera and then, we will also focus on some of these works using a high speed PIV PLIF and then, we will go in to understand force blow off and blow off in vitiated flows. So, then we will look into also blow off in swirl stabilized flames once again from Georgia Tech as well as from DLR growth.

So, these are the topics that we will covere, but this is of course outline, is an overall outline and we will spend quite some time on laser based diagnostics to understand what are the fundamental principles behind it because here we will talk about an unique situation, where we will use these diagnostics to essentially solve a particular problem that we encounter in combustion. So, we will understand, will solve how basically flame blows off in using this laser base diagnostic. So, how this flame blows up in a prototypical afterburner configuration, that is the whole aim.

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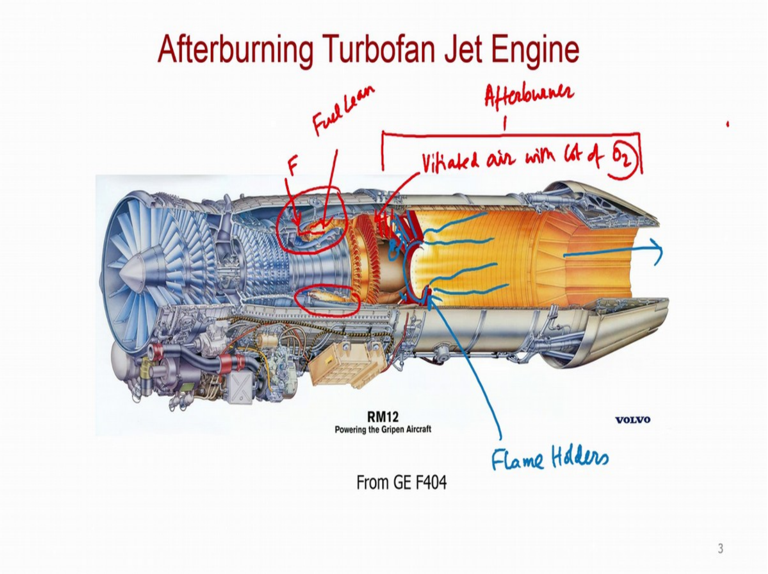

Afterburning Turbofan Jet Engine

From GE F404

So, this is how afterburning turbofan jet engine looks like. So, the previous jet engine that we had shown you that where the turbojet engine was essentially was an engine with which did not have this part. If you remember I will come to this part, but before that let me just once again describe to you. So, here you have in front you have the fans and then, you have the compressors, few stages of compressors and then, here you have the combustion chamber which we discussed so far that is this is a main gas turbine, this is the main combustion chamber, this is a main combustion chamber and this is essentially your fuel nozzle. So, the fuel is injected from here, the liquid fuel comes into through here and it is injected through here and it goes into a spray like this and it of course is small and this is your igniter which is placed here and then, of course the flow, the hot flow goes out and hits the turbine blades and turns the turbine blade which then the turbine blades in turn rotates the compressor blades because they are connected on the, mounted on the same string same shaft.

Now, what happens now in an ordinary like a commercial jet engine, you just now expand the flow through a nozzle and that is it, but here what you have is that you have this full thing which is called the afterburner and the decker. Why we need the afterburner is already described previously that sometimes in a situation where you need a very sharp climb, you need where the aircraft needs to climb very quickly where it needs to, it needs some extra thrust. So, then you turn this afterburner on which develops which burns the fuel in the oxygen reached in the oxygen rich vitiated here because as you remember here the burning happens in fuel lean.

So, the air that comes out here, the air that comes out here is the air is essentially vitiated because it contains products with lot of oxygen. So, what you do here is that the air that comes out of the turbine is essentially vitiated here. It contains products like CO2, CO, some amount of CO. It of course contains water vapor and it can contain some other pollutants in small amounts, but mainly it contains quite some amount of oxygen because what we had here was fuel lean combustion.

So, now what you do is that through these fuel spray bars, through these fuel bars, these are the fuel bars you basically inject the fuel and then, these fuels forms of fuel are mixture here. This fuel mixes with the air here and in these regions and the flame essentially can be stabilized like this. This we got are afterburners you see here. So, this is the flame holders. Essentially these are the things of the flame holders and the flame is in the wake region of this flame holder, this bluff body flame holder. The flame is stabilized and then, of course you expand it to a nozzle to develop the thrust, ok.

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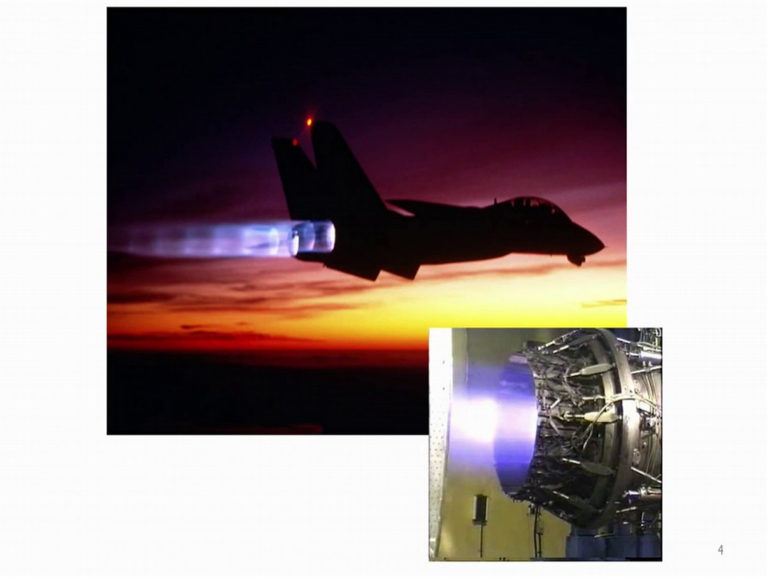

So, then we go onto this thing. So, this is how our flame in an afterburner look like. So, of course the aircraft is moving in this direction and the flame as you see goes out here and this is from a cavity engine afterburner that you see here. So, exact nature of the flame depends on the state of mixing, but here you see a blue flame. So, often the flame actually is quite close to a premix flame because of the sufficient distance. If there is a sufficient distance between the fuel spray bars and the flame holders, then the fuel near mixing can be complete and of course, you see this is a very vitiated, strongly vitiated high temperature environment in itself. So, the liquid fuel can evaporate very quickly and if it mixes, it can essentially burn in a closed to premix mode, but of course we will see lot of like a yellow flames coming out of the afterburners also which shows that it is essential in non-premix mode.

So, this is what we are going to study that basically flames in afterburners now. So far we have studied a lot about combustion, but we have not really discussed any experimental techniques to major things in a combustion. Now, if you want to talk about measurements, the first question is that you want to measure in combustion. So, what is most important in combustion as we have discussed before in combustion is essentially stands on two pillars one is chemical kinetics and other is fuel fluid mechanics ok.

So, chemical kinetics essentially talks all about the different breakdown, how essentially the fuel breaks down into smaller and smaller units and then, it essentially oxidizes to form the products to a series of elementary reactions. So, in that sense we know that one of the most important things that we have come to learn using this chemical kinetics is the role of the intermediates, right, role of the radicals and as you see one of the most important intermediates in combustion is this hydroxyl radical is also very important to H atom and O atom is also important, but hydroxyl radical is also very important.

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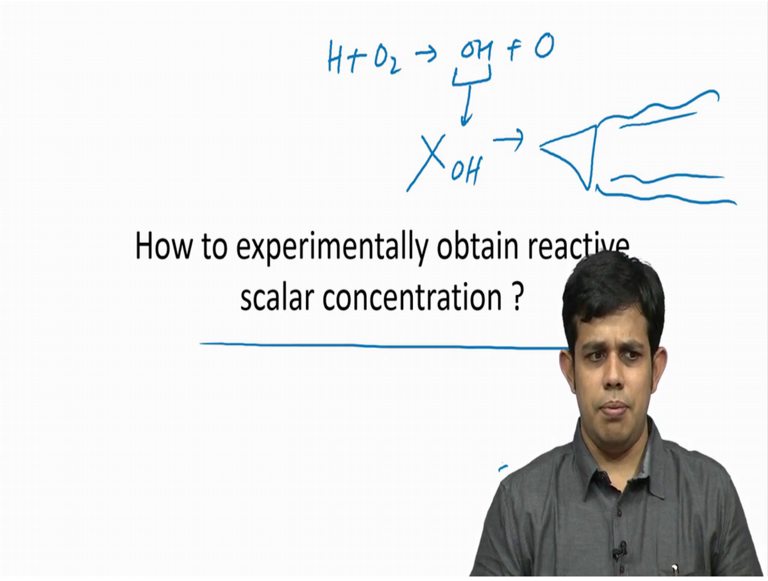

$H + O_2 \rightarrow OH + O$

$X_{OH} \rightarrow$

How to experimentally obtain reactive scalar concentration ?

So, if we can say that if the question arises that what do we experimentally, how to experimentally obtain the reactive scalar concentration or the first question is that what do you want to measure. Suppose then we want to measure, if that is the case suppose we want to a measure some radicals, so what is the most important radical. Of course, H can be a very important radical, but that is very hard to measure. O is also hard to measure. So, it is not only that you want to measure something important. It has to be measurable also and you have to measure it in a way so that you do not disturb the flow inside the combustor.

So, you cannot really have a probe, have a big probe. So, if you are sitting inside the combustor which distorts the flow itself, anything you see if I put a probe here, first of all putting a physical probe is difficult, but even in a normal laboratory setup if you want to put a physical probe here, that will disturb the flow. It will act like a bluff body and it can cause a lot of heat loss etcetera. So, we want to measure things in a non-intrusive manner that is we do not want to put a physical probe, but by shining light and by getting some signatures how some molecules interact with the light that we sent in, we want to measure their presence.

So, in a more formal language basically we want to measure the concentration of some active radicals, we want to measure the species concentration of some reactive scalars. So, which reactive scalar do we want as we remember that one of the most important reactions in combustion was H plus O2 going to H plus O. This was the most important in chain branching reaction that we encountered in and that we encountered in combustion. So, one of the product of this most important reaction is OH and let say one of the most important things we can measure in combustion which will tell us something about the kinetics, something where the reaction is happening, something where the flame is, that is where the flame is located.

So, if we we can say that where we have sharp increase in OH, we can say that the flame is located at that point. So, as a result of that it is worthwhile to measure OH concentration in a combustion environment. So, let say we want to measure the mole fraction of OH in a given flow. So, suppose we have a bluff body like this, the flow is coming here, the flame is stabilized like this. So, OH will be formed. Somewhere we want to measure OH concentration.

Now, how can we experimentally obtain this reactive scalar concentration? As I said we cannot really I mean put a physical probe inside because the environment is also harsh and then, the actual measurements are difficult to obtain. So, let us say we want to talk about now that how can we measure, thus the concentration or the mole fraction of this hydroxyl radical using laser based diagnostics. So, that is the most important part of this class.

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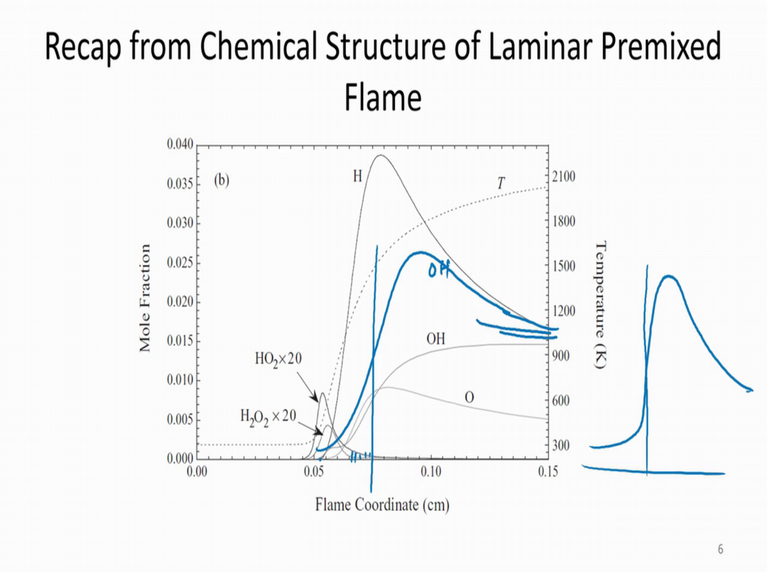

Recap from Chemical Structure of Laminar Premixed Flame

So, if you recap that to justify why we want to measure OH, you see this was the recap. This is a recap from the chemical structure of laminar premix flames which we discussed several weeks ago. So, this was the premix flame and this came from detail kinetics and this is the temperature and you see OH, this is the OH profile. Of course, you see that there is like this is actually OH profile in a hydrogen flame. So, in a hydrox if it in a methane flame, OH profile will look something like this, ok.

So, you will see that what is happening here is that this we have got some for downstream, we also have got OH, but the point where OH increases sharply, that can be essentially called the flame location. So, with the we can say that the maximum gradient of OH, we can say that the maximum gradient of OH essentially corresponds to my start of the flame that essentially corresponds to the flame front.

So, if I can measure OH, it can tell me two important things. It can tell me of the extent of the reaction on one hand of the most important reaction of H plus O2 going to OH plus O and on the second hand are the more importantly, it will tell me if I can identify the region where OH increases very sharply inside a flame, inside the flow. So, I can consider that contour which corresponds to the maximum gradient of OH to be essentially my flame front. Now typically in experiments you do not have a resolution of this order that is you do not have so high resolutions in in essentially turbulent flame experiment. So, this essentially looks like a very sharply, this OH essentially goes very sharply like this, ok.

So, we can essentially find out the maximum gradient of how OH is distributed in space in essentially to be space and from that we can find out the location of the flame. So, using OH we can very precisely and instantaneously using OH if we can have OH concentration, the distribution of OH concentration enough in space, in the field, distribution of OH in space in a combustor, then from that we can easily find out the location of the flame. So, that is very important and then from that we can find out how the local flow field looks like etcetera and also, it will tell you how the extent of the reaction happens in this kind of environment.

So, this is OH measurement. Measuring OH has been a very important activity of combustion researchers for quite some time.

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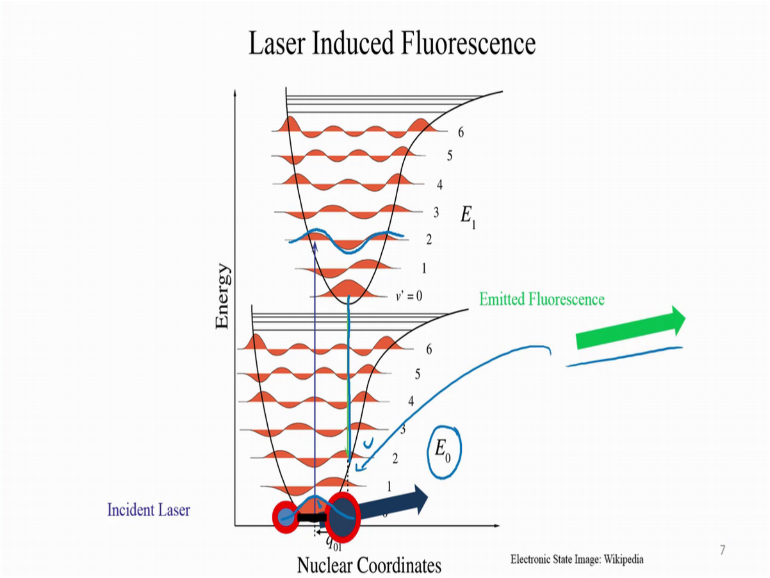

Laser Induced Fluorescence

Electronic State Image: Wikipedia

So, let us see what the basic principle behind OH is. So, OH we can measure with the concentration of OH of the hydroxyl radical using this principle called laser induced fluorescence . It is essential and experimental technique involving fluorescence and what we have here is that we will use this principle, we will use this technique of laser induced fluorescence to measure the concentration or the mole fraction of OH.

Now, how this is done. So, as you see here, let us consider that this is essentially OH radical, this is H, this is O and it is essentially like a lower energy state, lower electronic state given by E0 and this is how potential will look like and in this electronic state, there are like several other states of like rotational states, vibrational states and these are corresponding wave function. Now, this will involve a little bit of like terms from quantum mechanics etcetera. I am just using them here for the sake of completeness and this in a very basic, in a very simplified manner I will try to introduce what laser induced fluorescence is, ok. So, please bear with me.

So, this is a row vibrational, this is the electronic ground state and these are this nu double dash 0123 and these are the different vibrational states and these are the different vibrational wave functions. So, now suppose this OH molecule is residing at a ground state at nu dash double dash equal to 0, now when suppose there is an incident laser that comes in light. So, the light, OH absorbs the light and it goes promoted to the higher energy state and then, what happens is that it interacts with the neighboring molecules or go under some interact some inter-system crossing and then, it gets in that higher electronic state. It goes down from the higher vibrational state in the higher electronic state, it comes down to a lower vibrational state in the higher electronic state and eventually because it is more stable at the lower electronic state, it comes down to the lower electronic state, but while coming down, it emits this excess energy in form of a photon and this photon is essentially the fluorescence, ok.

So, this is the principle of laser induced fluorescence. I will just repeat once again. So, this OH is residing at the lowest vibrational state of the lowest electronic state, incident laser comes, OH absorbs light promoted to a higher electronic state, inter system crossing goes down to the lower vibrational state to do the lower electronic state and while doing that it emits fluorescence. So, there are essentially this large jump that it makes and because of the large energy difference between the two electronic states, it essentially emits photon and that photon essentially lays the emitted fluorescence or the laser induced fluorescence that we are talking about, ok.

So, that photon essentially this essentially light, so you can collect this light using a photo multiplier or using CCD camera and that idea is that once you know the intensity of this light, you can correlate that intensity of the light with the population of OH radicals that was present in this ground state before it was hit with the laser. So, once again you see I will just repeat this because this is important. So, incident laser comes, this is OH radical or the OH molecule which was in the lower electronic state or the lower energy state. Laser comes in, it absorbs light to get promoted to higher electronic state, inter system crossing gets down to the rod electronic state, emits the fluorescence and then, once again coming back to the original state by intercepting crossings, ok.

So, these are not really important right now. These are different that is the transition within the same electronic states are not important, but there are two things here. Number one, you see that this energy level in this energy coordinate is much greater than this energy level. So, the energy absorbed is greater than the energy released in terms of photon and that is because some energy is lost in this inter system crossings. So, as a result of that because the emitted energy is less than the absorbed energy, the emitted wavelength in fluorescence laser induced fluorescence is always greater than the absorbed wavelength.

Now, there are several questions that what determines that whether this OH will absorb the light and will get promoted to the higher electronic state. It is not if you have once area OH performed in a flame and we shine just normal light into it, of course it is not going to absorb and show you the fluorescence. So, there are specific rules by which OH can absorb a given light or given wavelength of a given light or OH can observe wavelength and basically it depends on the energy and essentially it means it comes down to the fact that this wave function that you have here and this wave function that we have here, they should have significant overlap.

So, the promoted state wave function and the ground state wave function if they have similar, if they overlap, then OH is in a conducive state. We absorb the photon or absorb the incident laser beam and it can get promoted and once it get promoted, it is of course it will come down and while coming down, it emits the fluorescence and if we can collect that light and then, that light we can essentially correlate it to the number of OH molecules that are present, ok.

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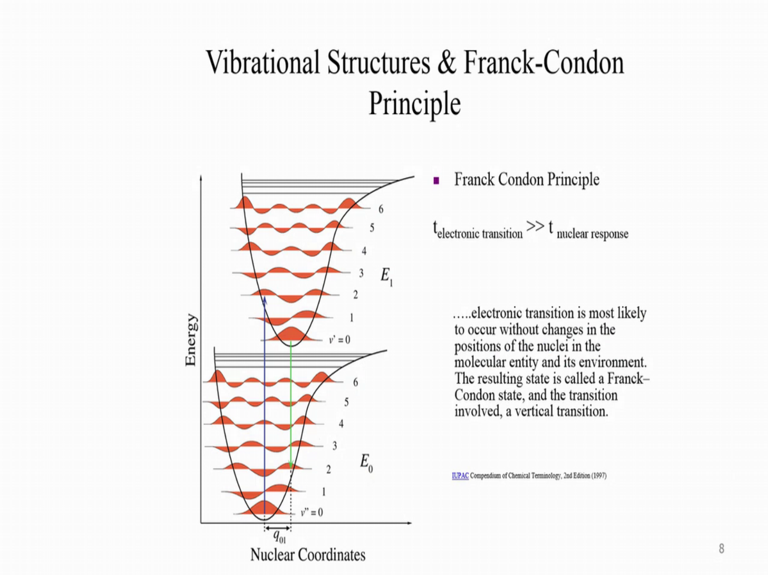

Vibrational Structures & Franck-Condon Principle

- Franck Condon Principle

$t_{\text{electronic transition}} >> t_{\text{nuclear response}}$

…..electronic transition is most likely to occur without changes in the positions of the nuclei in the molecular entity and its environment. The resulting state is called a Franck–Condon state, and the transition involved, a vertical transition.

IUPAC Compendium of Chemical Terminology, 2nd Edition (1997)

So, one principle that we have there is assumed in this laser induced fluorescence is essentially called the Franck Condon Principle and it means at the time for electronic transition is much greater than the nuclear response which means that the nucleus of this OH does not change orbitals, do not move while this electronic transitions happen, that is the electronic transition is most likely to occur without changes in the position of the nuclei in the molecular entity and this environment and the resulting state is called the Franck Condon State and the transition involved is a vertical transition. Otherwise if this is the nucleus is moved during this transition happening, then this we could not have overlapped these two potential. So, this is just a basic principle.

Now, in the next class we will come down and we will come back and discuss more about this laser induced fluorescence and quantitatively how we can extract by collecting the light from the intensity of the light, how we can tell that the intensity of a light corresponds to what mole fraction of OH because that is the thing, right. So, essentially what it means that we have a flame, we have shining light, shining a laser light at a particular wavelength, we need to shine it at a particular wavelength and that is why we need a laser.

So, the light shines on the molecules of OH that is present inside, the OH absorbs, get promoted to an excited state and undergo some inter system crossings and then, it gets demoted to this lower electronic state and while it gets demoted because of the energy level difference, it gives out a photon and this photon we can collect and by the number of photons that is being collected which is essentially the intensity of the light, we can correlate it to the mole fraction of OH that was present at the time when this laser light hit OH in first place. So, that is essentially the number of OH molecules or the mole fraction of OH molecules that is present in my flame. So, that is what I want you to know and we will go into a little bit of details that how we can find that out. So, that will be done in the next class.

Thank you.