Combustion in Air Breathing Aero Engines

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Lecture - 62
Review

Hello friends, welcome back. So, in this lecture, I will just go over all the topics or just the name of the topics that we have covered. In this your 12 week long course and so, this course was on combustion in air breathing aero engines.

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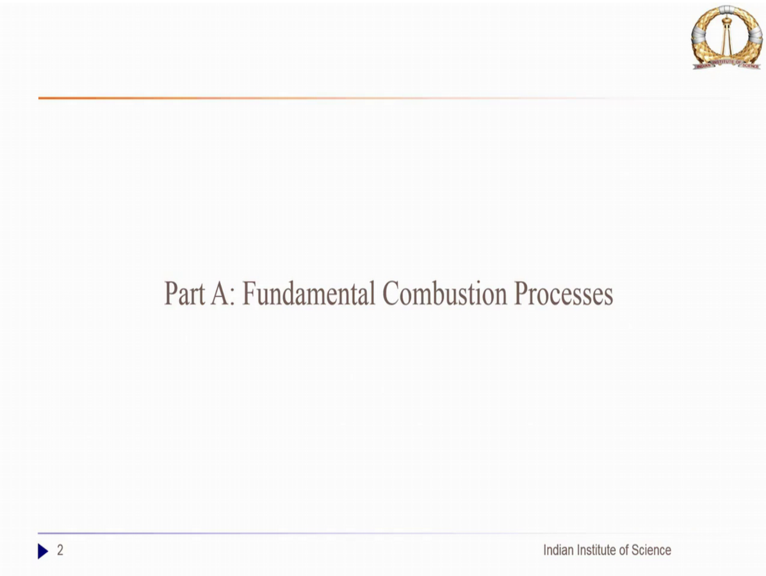

And of course, you know combustion in air breathing aero engines is a complicated phenomena by now, but it has got several aspects to it. It has got the design aspects where you have to think about designing a combustor that can power our gas turbine engine or it can power a scramjet or a ramjet engine and but those design aspects are intricately coupled to the fundamental processes that happens in the combustor. So, to design a combustor which is working, which is successful, which is efficient, one needs to know the fundamental combustion process is very very well.

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No.	Module	Topic	Concepts
1	Chemical Thermodynamics and Kinetics	Introduction	Aero Propulsion, Liquid Hydrocarbons, Energy Density
2		Chemical Equilibrium I	Classical Thermodynamics; Gibbs Free Energy; Chemical Equilibrium; Equilibrium Constants
3		Chemical Equilibrium II	Heat of Formation; Sensible Heat; Heat of Reaction & Combustion; Heat of Reaction from K_p; Adiabatic Flame Temperature
4		Chemical Kinetics I	Law of Mass Action; Reverse Reactions; Net Rate of Reactions;
5		Chemical Kinetics II	Multiple Reactions; QSS & PEA approx; Reaction Order & Molecularity; Arrhenius Law; Activation Energy; Collision Theory
6	Combustion Kinetics of Practical Fuels	Chemical Kinetics III	Collision Theory
7		Chemical Kinetics IV	Transition State Theory; Lindemann Theory (Unimolecular Reactions); Straight Chain Reaction; Hydrogen-Halogen Systems; Branched Chain Reaction; Flame Inhibitors; Experimental Techniques
8		Oxidation Mechanism of Fuels I	Practical Fuels; Ignition Delay
9		Oxidation Mechanism of Fuels II	Branched Chain Reaction; Oxidation of H_2-O_2 System(Z-curve); Oxidation of CO; Role of Initiation Reaction
10		Oxidation Mechanism of Fuels III	HC Oxidation; Methane Oxidation; Ignition of Large HC (Cool Flame and NTC); β-Scission Rule
11		Oxidation Mechanism of Fuels IV	Formation of NO_x & its Control; Soot and PAH Formation; Mechanism Reduction
12	Transport Processes and Governing Equation	Transport Phenomena	Introduction & Phenomenology; Diffusion Coefficients & Derivation; Non-dimensional Numbers; Kinetic Theory
13		Governing Equations I	Introduction; Control Volume Formulation; Reynolds Transport Theorem
14		Governing Equations II	Constitutive Relations; Diffusion Velocities; Auxiliary Relations; Isobaric Assumption
15		Governing Equations III	Simplified Diffusion Controlled System; Energy Equation
16	Coupling Functions and Laminar Non-Premixed Flames	Governing Equations IV	Energy Equation in Enthalpy Form; Species Transport; Distinct Specific Heat & Diffusivity Formulation; Characteristics of Simplified Eqns.; Conserved Scalar Formulation
17		Governing Equations V	Derivation of Coupling Functions; Local Coupling Function Formulation
18		Laminar Non-Premixed Flames I	Structure of Chambered Flame; Concepts from Coupling Function
19		Laminar Non-Premixed Flames II	Review of Chambered Flame & Coupling Function; Reaction Sheet Approximation & its Properties
20		Laminar Non-Premixed Flames III	Condensed Fuel Vaporization
21		Laminar Non-Premixed Flames IV	d^2 Law of Droplet Vaporization
22	Laminar Premixed Flames	Laminar Premixed Flames I	1D Wave Structure; Rankine-Hugoniot Relations
23		Laminar Premixed Flames II	Detonation and Deflagration Waves
24		Laminar Premixed Flames III	Structure of Standard 1D Flame; Scaling Analysis; Burning Flux and Pressure
25		Laminar Premixed Flames IV	Analysis-Governing Equations; Cold Boundary Difficulty
26	Premixed Combustion: Analysis, Chemistry and Limit Phenomena	Laminar Premixed Flames V	Zeldovich Frank-Kamenetskii Solution
27		Laminar Premixed Flames VI	Determination of Laminar Flame Speed; Flame Speed Dependences; Extraction of Global Parameters
28		Laminar Premixed Flames VII	Asymptotic vs. Chemical Structure; H_2-air Flame Diffusive Reactive Structure; Chain Structure; Thermal Structure
29		Limit Phenomena I	Concepts of Ignition and Reaction; Quenching Distance & MIE; Adiabatic Thermal Ignition; Non-Adiabatic Explosion; Well Stirred Reactor; S-curve
30		Limit Phenomena II	Premixed Flame Extinction; Flammability Limit;

So, that is why we have gone into this whole course, essentially could be split up into 3 parts, the first part, we would have discussed fundamental combustion processes. So, if you remember. So, here we have the modules, we have the topics in this the first column is the number of serial number of the lectures. Second column is the module it covered, third column is the topic it covered and fourth column is the concepts that we covered. So, in this module chemical thermodynamics in kinetics which was about 5 lectures.

We first of course, give the introduction about the importance of liquid of combustion air breathing aero engines and it is how it is coupled to the high energy density of the liquid hydrocarbons then in chemical equilibrium, we went into the topics of classical thermodynamics, maximization of entropy principle; Gibbs free energy, we talked about chemical equilibrium, the equilibrium constants KPKC, if you remember and then we looked into different things like heat of formation and we discussed, what is the sensible heat, what is heat of reaction and combustion we also discussed the concepts of sensible enthalpy and enthalpy of formation.

So, those things are very important whereas, the total enthalpy is a sum of the sensible enthalpy and enthalpy of formation, we discussed heat of reaction and combustion and we said how we can estimate heat of reaction from the equilibrium constant and then how we defined; how we could estimate adiabatic flame temperature for a closed vessel which does not interact with the surroundings through energy transfer where and we showed that how adiabatic flame temperature concept essentially emerges from the concept of the conservation of energy.

So, then we looked into chemical kinetics, we looked into the law of mass action which is the; we are founding pillar of a chemical kinetics. We looked into reverse reactions, we need to look into net reactions and we looked into this multiple reactions, how to handle multiple reactions, the quasi steady state and the partial equilibrium approximations. We looked into reaction order of molecularity, we looked into Arrhenius law activation energy and collision theory, then we looked into this; the concepts of activation energy which comes in the Arrhenius law where we said that which was like the your K; K is equal to e to the power of b times e to the power of alpha times e to the power of minus activation energy by r t and then the whole reaction rate becomes essentially, this K, the reaction rate constants times the product of the concentration of the reactants raised to their stoichiometric exponents.

So, all these we discussed, we discussed how we can estimate this reaction rate constant by rudimentary idea called collision theory which does not take into account the energy states of the of the electron cloud surrounding their molecules and as a result we looked into this more advanced transition state theory where by invoking these 2 step reactions forming formation of an activated complex, we could form a better description of the reaction rate constant.

We looked into in molecular reaction stretch in reaction hydrogen halogen systems branch in reactions, this was very important where we showed that under what conditions, a system can lead to very rapid combustion that is when these branching reactions can dominate and it can produce more and more chain carriers then and what are the criteria fraught that and we also looked into the flame in inhibitors and experimental techniques to measure the different reaction rate constant reaction rate constants. Then we looked into oxidation mechanisms of fuels; practical fuels, we define what is ignition delay, we looked into branch chain reactions, the hydrogen oxygen systems, Z curve, we looked into the competition between termination and the branching reactions which could defined 1 of the limits. We looked into oxidation of carbon monoxide and the role of initiation reaction.

We looked into methane oxidation ignition of light hydrocarbons and the phenomena that it entails like cool flames and negative temperature coefficients; how the bond breaks in different hydrocarbons beta session rule formation of Nox Zeldo which mechanism prompt Nox, etcetera. Those things that we discussed, the concepts of soot and power formation in a very little bit tangential manner, you know very quick manner, we discussed. Also we discuss very few aspects of the mechanism reduction. So, then with this, we were equipped with chemical thermodynamics and kinetics in this part. Next we looked into transport phenomena and governing equations, we looked into different forms of transport a momentum transport heat transporter as well as species transfer and the associated diffusion coefficients and derivations.

And how we can use the kinetic theory to discuss then we looked into the governing equations, we showed that the all fundamental go up like conservation laws which are used to describe systems are essentially written for systems. So, then for systems; how we can translate those laws for closed systems to open systems like the flowing systems which are of interest for engine type of configurations and that was done by the Reynolds transport theorem.

So, that lead to this control volume formation and there is Reynolds transport theorem, then we looked into different constitutive relations that is after you derived the governing equations for control volumes your job does not end because there are several other equations and relations that needs to be supplied to basically to close the system of equations. We looked into diffusion velocities an ancillary relations and isobaric assumption and we looked into simplified this diffusion control systems and energy equations. And then we derive the energy equation in the enthalpy form, we derived the species transport equations and we derived the incorporated different ways by which we could simplify this reaction systems.

Simplify this governing equations by invoking the distinct diffusivity and the distinct specific heat and diffusive formulations and this led to simplified equations and to, but then after this will arrived at the simplified equations we realize that this non-linear reaction rate term creates a very big problem. So, we try to derive conserved scalar equations formulation by which we could as derive a system of equations which describes the concept scalar where there is no such right hand side source or sink term, but of course, the we realize that this could not be avoided. So, in one equation you have to solve for the reaction rate because in a combustion system of course, that is the what is the most important and then we looked into the derivation of coupling functions local coupling function formulation, then we moved into non premix flame, we looked into the structure of a 1 b chambered flame which is an which can be considered as any unit or the most fundamental of non brimming flames by using concepts of coupling functions which.

So, we reviewed the chambered flame and the coupling functions and invoked the reaction sheet approximation and its properties then we looked into condense fuel vaporization because as we know that all these engines use liquid fuels. So, it is important to understand; how this liquid fuels can evaporate and then mix and then react because in air breathing aero engines, the reactions invariably happens in gas phase. So, it is imperative to know; what is the mechanics and what is the heat transfer thermodynamics behind this liquid fuel evaporation and burning.

So, we looked into the D square law of droplet vaporization also then we moved into laminar premix flames where we looked into the first term, we looked into the thermodynamics of laminar premix flames is Rankine Hugoniot relation. We defined out the difference between deflagration and detonation and what are the; how does the properties before and after change for these kinds of different waves deflagration and detonation waves then we looked into the structure of standard 1D flames, we invoke the scaling analysis.

And we found out the burning flux and as a function of pressure and we need found out that how burning flux is one of the most important properties of that defines the laminar premix flame and what does it depend on, then we looked into analysis and governing equations. We looked into the pole boundary difficulty which happens when you want to solve for a 1D premix flame in a double; in finite domain then to define to arrive at these things; at this burning flux, analytically we invoked; we took up this as Zeldervich Frank Kamenetskiis and then we looked into the laminar flame speed the different-different types of flames you dependence; how we can extract global parameters from overall complex set of reactions.

We looked into the chemical structure of hydrogen of flame, chain structure, thermal structure and then we looked into the limit phenomena ignition, extinction quenching distance adiabatic thermal ignition, non adiabatic explosion and then well stirred reactor and its curve by explosion. Once again here we mean rapid combustion where the rapid release of energy causes quick increase in temperature and then we looked into the well stirred reactor and the S-curve and the different like ignition extinction points at different damn coolant numbers then we looked into the limit frame of A.

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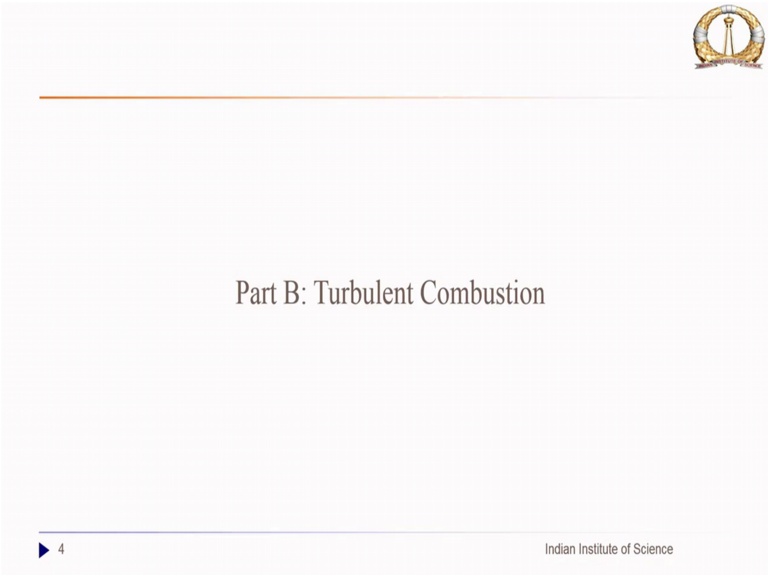

Now, we looked into premiums from extinction; how does it extinguish and the flammability limits. So, with this, our concepts of this fundamental combustion process was done and then, we were in a position to understand turbulent combustion because you see in an engine is a very complex turbulent flame so, but the individual unit part of a turbulent flame is essentially this fundamental combustion process that we have described.

So, once we know the fundamental combustion processes, we can use those concepts to describe something bigger, something statistically to describe turbulent combustion. So, then we looked into turbulent combustion where we first started with non-reacting and reacting turbulent flows.

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No.	Module	Topic	Concepts
31	Non-reacting and Reacting Turbulent Flows	Introduction to Turbulent Flows	Introduction to Turbulence; Characteristics; Lorenz System; Probabilistic Description
32		Non-reacting Turbulent Flows I	RANS Eqns.; Statistics; Turbulent Kinetic Energy Transport Equation
33		Non-reacting Turbulent Flows II	Turbulence Scales & Energy Cascade; Kolmogorov Hypothesis; Energy Spectrum
34		Reacting Turbulent Flows I	Effect of Turbulence on Combustion; Favre Averaging
35		Reacting Turbulent Flows II	Eddy Viscosity; k-ε Model; Energy Equation and Reactive Scalar Formulation
36	Turbulent Non-Premixed Flames	Reacting Turbulent Flows III	Moment Methods; Closure Problem, Chemical Source Term Averaging Problem
37		Reacting Turbulent Flows IV	Dissipation and Scalar Transport; Gradient Transport; Reactive Scalar Transport Eq. Scalar Dissipation Rate
38		Reacting Turbulent Flows V	Eddy Breakup and Eddy Dissipation Models; Spalding Theory
39		Turbulent Non-premixed Flames I	Introduction; Types of Non-premixed Turbulent Flows; Mixture Fraction Space
40		Turbulent Non-premixed Flames II	Transport Eqn. for Z; Presumed shape PDF Approach; Favre Averaged Equations
41		Turbulent Non-premixed Flames III	Crocco Transformation into Z Space; Transformed Energy Equation and SDR; Timescales in Non-premixed Combustion; CMC; Regimes of Non-premixed Combustion
42	Turbulent Premixed Flames	Turbulent Premixed Flames II	Regime Diagrams; Interpretation of Da and Ka; Other Flame Speed Definitions; Flame Stretch
43		Turbulent Premixed Flames III	G-equation and Models for Flame Speed in G-equation
44		Turbulent Premixed Flames IV	G-equation; Turbulent Burning Velocity; Turbulent Flame Speed Derivation
45		Turbulent Premixed Flames V	Experiments; Turbulent Flame Propagation Rate; Contemporary Experiments
46		Turbulent Premixed Flames VI	Introduction to Bray-Moss-Libby Model

If we looked into turbulence first where we spent a lot of time in analyzing the non reacting turbulence concepts, we looked into how we can derive dance equations, how does the concepts of a turbulent kinetic energy transport equation arrive, what are the co; how does production of turbulent kinetic energy happen, how does dissipation happen and then once this turbulent kinetic energy is produced, how does this pass across different scales and gets dissipated into the Conmebol of length scales.

So, we looked into the effect of we looked in this turbulent kinetic energy and cascade we looked into Kolmogorov of an all hypothesis and we looked onto the energy spectrum, we looked into the turbulence effect of turbulence and combustion and we introduced the concept of Favre averaging or density weighted averaging and then we looked into this eddy viscosity K S model and there energy equation and reactive scalar formulations then we looked into the moment methods.

Where we wanted to average would arrive at averaged description of this governing average governing equations or governing equations that describe average variables, but immediately we landed up in a closure problem and we found that the non-linearity of the of the reaction rate problem of non-linear rate of the reaction rate poses a major difficulty in its averaging. So, then we looked into the dissipation and scalar transport. We looked into the gradient transport and the reactive scalar transport and scalar dissipation rate and we looked into rudimentary models to provide closures where we discussed like eddy breakup and eddy dissipation models where Spalding's theory of Ebu Eddy break up concept, we looked into then turbulent non premixed combustion where we showed different types of non premixed turbulent flames and then we introduced the concept of mixture fraction and once the mixture fraction concept of in was introduced as a conserved scalar, we also discussed the average; the transport equation for Z and to close them; how one can use this PDF presumed shape, PDF approach and the Fabri averaged equation.

Then we because this mixture fraction emerges there is such an important quantity, we said that one could even transfer or one could even write the governing equations with mixture fraction as the independent variable. So, that led to this Croco transformation in the Z space. So, we transformed all these energy equations into mixture fraction space that led to the emergence of the scalar dissipation rate as a characteristic diffusivity and then we discuss the different time scales in non premix combustion, we will touch upon conditional moment closure modelling and we touched upon also the regimes of non premix combustion.

So, with that we went into turbulent premix flames where we discussed at length; the concepts of regime diagrams; the interpretation of the Damkohler number call of its number that the flame speeds and the flame stretch concepts we looked, we showed the G equation and the models for flames with in G equation and then we looked into the turbulent burning velocity and the turbulent flame derivation we showed the experiments of turbulent flame propagation rate contemporary experiments and we finished it off with the bray moss and Libby model.

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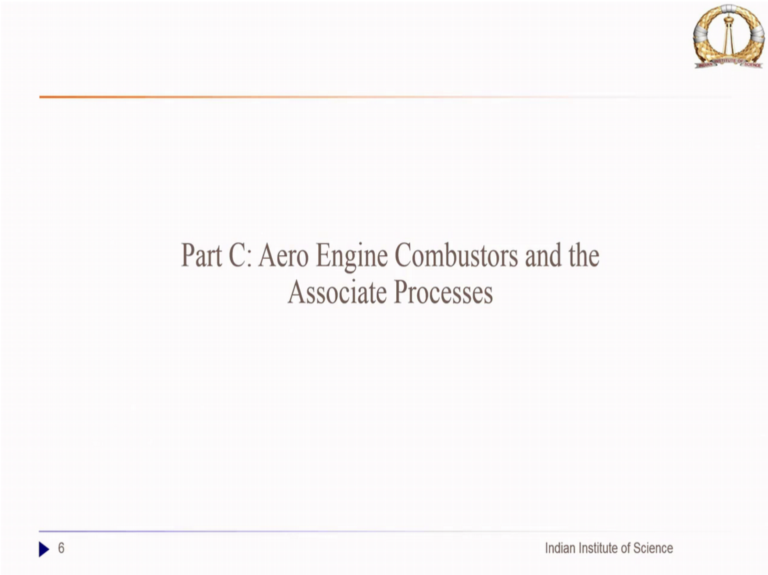

Now, this was the final part. So, we now have understanding of the fundamental process of combustion we know how we can describe a turbulent combustion using this part. So, now, we can go into the different applied aspects of our aero engine combustors and the associated processes. So, the whole thing is that the combustion happens in these; all this engine set intensely turbulent flows. So, it is important to understand the fundamentals to have been appreciate what happens in a gas turbine engine and to develop capabilities on how to model them.

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No.	Module	Topic	Concepts
47	Aero Gas Turbine Combustors	Aero Gas Turbine Combustors I	Introduction; Basic Design Features; Different Zones in a Combustor
48		Aero Gas Turbine Combustors II	Types of Combustors; Can; Can-annular; Annular Combustors; Flames in Swirling Flows
49		Aero Gas Turbine Combustors III	Different Zones of Combustors; Swirling Flows
50		Aero Gas Turbine Combustors IV	Liquid Jet Breakup; Rayleigh-Plateau Instability
51		Aero Gas Turbine Combustors V	Atomizers, Cooling Techniques
52	Flame Stabilization	Understanding Flame Stabilization and Blow-off in Prototypical Afterburners using Laser Diagnostics I	Afterburners, Introduction to Bluff Body Flows, Blow-off Correlation
53		Understanding Flame Stabilization and Blow-off in Prototypical Afterburners using Laser Diagnostics II	Laser Induced Fluorescence (LIF)
54		Understanding Flame Stabilization and Blow-off in Prototypical Afterburners using Laser Diagnostics III	Particle Image Velocimetry, Blow-off Stages, Blow-off Mechanism from Small-scale Experiments
55		Understanding Flame Stabilization and Blow-off in Prototypical Afterburners using Laser Diagnostics IV	Blow-off Mechanism using Laser Diagnostics from a prototypical Afterburner
56	Combustion in Scramjet	Combustion in Scramjet I	Introduction to Scramjets
57		Combustion in Scramjet II	Steady 1D Analysis of Frictionless Flow with Heat Addition in Constant Cross-section
58		Combustion in Scramjet III	Different Processes in Scramjets: Mixing
59		Combustion in Scramjet IV	Ignition and Burning Time Scales, Flame Stabilization
60		Review	

So, of course, the most; one the most important engines around is the gas turbine engine and we looked into the aero gas turbine combustors. So, where we looked into the; we introduced it.

We introduced it; the basic design features and how the modern gas turbine combustor essentially evolves from a straight duct, why it needs a diffuser, why it needs a flame solars, all these things and then we looked into the different zones in a combustor, we looked into the different types of combustors, can annular combustor and we looked into the flames installing flows and then we looked into the different zones of the combustors, the primary zone, the dilution zone, the primary zone and the valuation zone mainly. And how those can be used couple to achieve a desired pattern factor which is very important for the life of the turbine, but of course, so, this aero gas turbine engines works on the prints are works with liquid fuels.

So, it is important to understand how liquid jet breaks up because. So, far we have understood how the droplet evaporates so, but taking a step back. Now we needed to understand how the liquid jet essentially breaks up. So, that the surface area can be increased by forming small droplets and now the small droplets can evaporate and mix and burn.

So, for that liquid jet breakup, we looked into Rayleigh plateau instability, the fundamentals and then we looked into different atomizers and cooling techniques. So, from photo in the following; then we looked into flame stabilizations and for that we introduced afterburners and we introduced after bluff body flows and the different blow off correlation, we discussed at length the principles and the applications of laser induced fluorescence that is we need to understand how the species field evolves inside a inside a real combustor.

So, for that one of the ideal techniques is to use the laser induced fluorescence or and it is a planar counterpart on the plane or laser induced fluorescence. Also we looked into particular image velocimetry, we looked into the different blow off stages; the particle image velocimetry was used to understand the flow field of this combustion inside the combustor in the flow field you know in a flame which is stabilized by a bluff body, then we looked into the different blow off stages, we looked at the blow of mechanisms and that emerges from the small scale laboratory experiments.

And then we discussed the blow of mechanism using laser diagnostics from a prototypical afterburner that was this experience had done at university of Connecticut and finally, we looked into this scramjet combustion in scramjet, where we introduced the scramjet, we introduced steady one the analysis of frictionless flow with heat addition in constant cross section, we looked into different processes in our scramjet like mixing and then we looked into ignition burning time skills and flame stabilisation. So, that is all we have covered for this course. It is a lot of material that we have covered.

And I hope that you will find this useful and find it exciting to pursue one of these or many of these topics further in your career.

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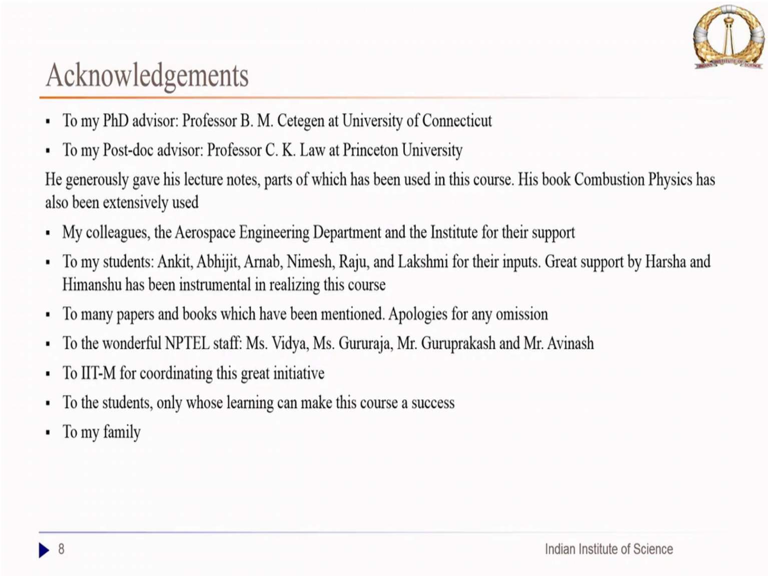

So, I will finish off with these acknowledgements. First of all thanks to my PhD advisor Professor B M Cetegen, I have presented many of the works that we did together at University of Connecticut to my post doc advisor Professor C K Law at Princeton University and many of the notes; he generously gave and which I have taken some parts of that and have been modified them and used this in this course of course, with his permission.

And then my colleagues, the Department of Aerospace Engineering and the Institute for their support, to my students acknowledgments is due are due to my students on Ankith, Abhijith, Arnub, Nimesh, Raju and Lakshmi for their inputs and of course, my PhD students Harsh and Himanshu has been instrumental in realizing in this course in making

many of the slides, editing them, modifying them as well as preparing them as well as with the assignments and the question papers, their help is acknowledged and too many papers and the books that have been used.

We have used numerous materials from numerous papers and books with citations of course, if there are any omission, apologies for that and to the great wonderful and NPTEL stuff, Miss Vidya, Miss Gururaja, Mister Guru Prakash and Mister Avinash who have patiently done worked with me throughout this course, to IIT Madras for coordinating this great initiative, to ISC for coordinating this great initiative and of course, acknowledgements are due to you to the students only whose learning can make this course the success, and finally acknowledgments to my family for their patience.

Thank you very much. Hope you enjoyed this course.