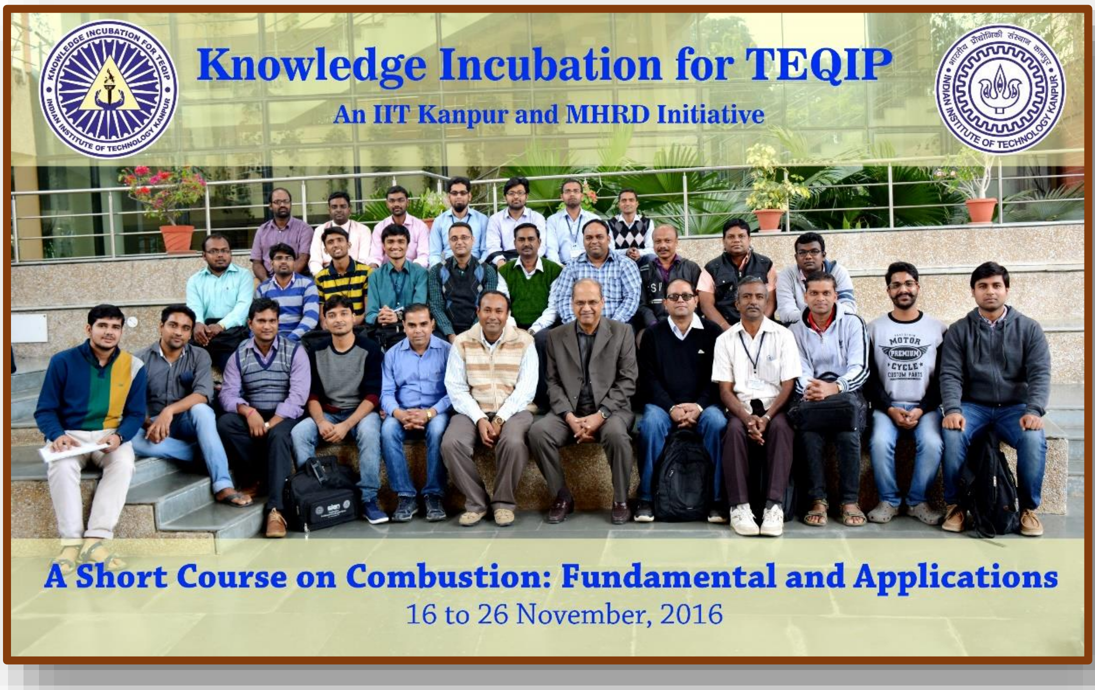
A Short course on Combustion: Fundamentals and Applications

November 16 - 26, 2016



KIT joined hands with GIAN to organize this 10 day course on fundamental and applications of combustion to encourage teachers and students of TEQIP institutes to be part of this course and enrich their fundamental understanding of combustion and its potential applications and challenges in the development of modern combustor systems for transportation, power-generation and other industrial applications. Keeping in mind that a better understanding of combustion processes is essential to improve the design of industrial combustion systems by enhancing the flame stability, improving the combustion efficiency, and reduction in pollutant formation; the course emphasized on why it is essential to study combustion and how it represents an area offering many challenges and opportunities for fundamental research. There were total of 40 hours of lectures and an additional 6 hours of hands-on laboratory sessions. The lectures were delivered by experts from IIT Kanpur and Prof. Suresh Aggarwal from University of Illinois, Chicago. At the end of the course there was a test to assess its impact on participants.

TOPICS DISCUSSED

1. Thermochemistry: Thermodynamics of a Reacting Mixtures

- Introduction to combustion, flames and fuels
- Thermodynamic or state properties of a reacting mixture
- Concept of equilibrium
- First law of thermodynamics, internal energy, work, enthalpy
- Heat of combustion, heating value of fuel, adiabatic flame temperature
- Chemical equilibrium, Second law of thermodynamics, entropy, Gibbs free energy, equilibrium constant
- Calculation of equilibrium composition and temperature, use of chemical equilibrium software.

2. Chemical Kinetics and Reaction Mechanisms

- Introduction, various time scales, Damköhler number
- Law of mass action, reaction rates for single reaction and multiple reactions
- Forward and backward reactions, state steady approximation, equilibrium constants
- Elementary and global reactions, chain reactions
- Reaction mechanisms for the oxidation of hydrogen CO, and hydrocarbon fuels
- Mechanisms for NOx and soot formation

3. Governing Equations for Chemically Reacting Flows

- Convective and diffusive flux of mass, momentum, and energy
- Transport properties for a reacting mixture; diffusivity, thermal conductively, viscosity
- Molecular models for transport properties
- Species mass conservation and mixture mass conservation equations
- Momentum conservation equations
- Energy conservation equation (various forms)
- Governing equations for one-dimensional flow and axisymmetric jet flow
- Lewis number and Schmidt number, Shvab-Zeldovich form of the energy equation

4. Simplified Reacting Systems

- Ignition/Combustion in a constant pressure system and a constant volume system
- Combustion in a perfectly stirred reactor (PSR), and a plug flow reactor (PFR)
- Use of software package (CHEMKIN, etc.) to analyse above systems

5. Laminar Premixed Flames

- Nonpremixed, premixed and partially premixed flames
- Premixed flame speed, flame thickness, flame structure
- Dimensional (or scale) analysis of a premixed flame
- Simplified analysis of a premixed flame, effect of various parameters (pressure, temperature, equivalence ratio, fuel type, additives, etc.) on flame speed and thickness
- Flame extinction
- Detailed analysis of a premixed flame; Use of software package (CHEMKIN, etc.)

6. Laminar Non-Premixed (Diffusion) Flames

- Laminar Jet: flow characteristics, governing equations
- Qualitative analysis of a reacting jet, flame sheet approximation, flame shape and flame length, effects of various parameters (nozzle diameter, velocity, diffusivity, fuel type, etc.) flame length, methods for controlling the flame length
- Mixture fraction, concept of conserved scalar, governing (conservation) equation for the conserved scalar, state relationship, relevance of turbulent diffusion flames
- Opposed flow diffusion flames, flame extinction
- Jet flame lift off and blowout
- Pollutants formation in flames

7. Spray Combustion

- Droplet and spray modelling, Eulerian and Langrangian approaches
- Droplet evaporation and combustion
- Governing equations for two-phase flows
- Spray Combustion

LIST OF SPEAKERS

- Prof. Suresh Aggarwal, University of Illinois, Chicago, USA
- Dr. Abhijit Kushari, IIT Kanpur
- Dr. Ashoke De, IIT Kanpur

Workshop Organizers:

- **Dr. Abhijit Kushari**
  Department of Aerospace Engineering, IIT Kanpur

- **Dr. Ashoke De**
  Department of Electrical Engineering, IIT Kanpur

PARTICIPATING INSTITUTES

Institute	Number of Participants
AMU	3
NIT Kurukshetra	1
NIT, Jalandhar	2
FET MJP Rohilkhand University	2
Coimbatore Institute of Technology	1
Government College of Technology Coimbatore	1
Pondicherry Engg. College	1
NIT Jamshedpur	1
MNNIT, Allahabad	1
BIET Jhansi	1
NIT Calicut	1
Total	**15**

Workshop Schedule

November 16, Wednesday

Time	Event
3: 15 – 5:00	**Registrations**

November 17, Thursday

Time	Event
8:30 – 9:30	**Inauguration**
9:30 – 10:45	**Introduction, Thermochemistry: Classical thermodynamics for reacting mixtures** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Introduction, Thermochemistry: Classical thermodynamics for reacting mixtures** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Introduction, Thermochemistry: Classical thermodynamics for reacting mixtures** *Dr. Abhijit Kushari*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Introduction, Thermochemistry: Classical thermodynamics for reacting mixtures** *Dr. Abhijit Kushari*

November 18, Friday

Time	Event
9:30 – 10:45	**Introduction, Thermochemistry: Classical thermodynamics for reacting mixtures** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Chemical Kinetics** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**

14:00 – 15:15	**Chemical Kinetics** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Chemical Kinetics** *Prof. Suresh Aggarwal*

<u>November 19, Saturday</u>

Time	Event
9:30 – 10:45	**Chemical kinetics and Reaction mechanisms** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Chemical kinetics and Reaction mechanisms** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Chemical kinetics and Reaction mechanisms** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Chemical kinetics and Reaction mechanisms** *Prof. Suresh Aggarwal*

<u>November 20, Sunday</u>

Time	Event
9:30 – 10:45	**Simplified reacting systems** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Simplified reacting systems** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**

14:00 – 15:15	**Simplified reacting systems** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Mass transport, Governing equations for a chemically reacting flow** *Dr. Ashoke De*

November 21, Monday

Time	Event
9:30 – 10:45	**Mass transport, Governing equations for a chemically reacting flow** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Mass transport, Governing equations for a chemically reacting flow** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Mass transport, Governing equations for a chemically reacting flow** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Mass transport, Governing equations for a chemically reacting flow** *Prof. Suresh Aggarwal*

November 22, Tuesday

Time	Event
9:30 – 10:45	**Mass transport, Governing equations for a chemically reacting flow** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Laminar premixed flames** *Prof. Suresh Aggarwal*

12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Laminar premixed flames** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Laminar premixed flames** *Prof. Suresh Aggarwal*

<u>November 23, Wednesday</u>

Time	Event
9:30 – 10:45	**Laminar premixed flames** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Laminar premixed flames** *Prof. Suresh Aggarwal*
12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Laminar premixed flames / Laminar diffusion flames** *Prof. Suresh Aggarwal*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Laminar diffusion flames** *Dr. Ashoke De*

<u>November 24, Thursday</u>

Time	Event
9:30 – 10:45	**Laminar diffusion flames** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Laminar diffusion flames** *Prof. Suresh Aggarwal*

12:30 – 14:00	**Lunch Break**
14:00 – 15:15	**Laminar diffusion flames** *Dr. Abhijit Kushari*
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Laminar diffusion flames** *Dr. Abhijit Kushari*

<u>November 25, Friday</u>

Time	Event
9:30 – 10:45	**Pollutants formation** *Prof. Suresh Aggarwal*
10:45 – 11:15	**Tea Break**
11:15 – 12:30	**Pollutants formation** *Dr. Ashoke De*
12:30 – 14:00	**Lunch Break**
14:00 – 15:15	• **Droplet vaporization and combustion** • **Turbulent Combustion**
15:15 PM – 15:45	**Tea Break**
15:45 PM – 17:00	**Exam**

<u>November 26, Saturday</u>

Time	Event
9:30 – 12:30	**Certificate Distribution and Concluding Remarks**

SUMMARY of FEEDBACK

1. Given topic was:

- Too short: 1
- Right length: 24
- Too long: 1

2. In your opinion, was this course

- Introductory: 6
- Intermediate: 13
- Advanced: 5
-

3. Please rate the following

	Excellent	V. Good	Good	Fair	Poor
Course overall	9	11	5		
Course instructor	13	12	1		
Quality of presentation	9	13	4		
Course material	9	11	7		
Video and acoustics	7	10	7	1	

4. Would you recommend this course?

- Definitely not recommend: 1
- Unlikely to recommend: 0
- Recommend with reservations: 0
- Likely to recommend: 9
- Recommend with enthusiasm: 13

5. What are the strengths of the course?

- The experience of the professors which was shared during the course work was very effective.
- Course contents are properly chosen and are discussed in good length.
- This course started from fundamentals.
- Professors are well talented in the area of combustion.
- Good explanation of the topics with mathematics.
- Knowledge of the faculty. He has a big experience & incredible knowledge in this field.
- Faculty.
- Highly experience person like or Suresh Agarwal from which getting knowledge is very good for this course.
- The real time explanation & example with research (on-going & published)

- Extra ordinary numerical skills of the faculties handled strict time, proper presentations.
- Course focused on fundamentals aspects as well as numerical and practical application point of view.
- Explanation has been given from research work.
- Basic fundamental on the combustion.
- Course strength good all combustion fundamental are covered.
- Concept were made clear.
- Basic level understanding is mainly focussed.
- Course content having lot of experimental data.
- Duration is appropriate.
- Combustion is the key phenomenon in all the power generating systems and must be clearly understood.
- Results from experimental and numerical data.
- Scholar expertise plus knowledge in the area of subject, environment of course.
- Lectures delivered by researchers.
- Course instructions and material.
- At introductory level the course has been useful to get a good & complete grasp of combustion

6. How could the course be improved

- Can be go for advanced combustion.
- This course requires more teaching learning hours plus some more sessions on experimental and computational treatment of problems.
- Implements simulation work training.
- More practical session.
- If interactions made with more videos & images it will be better to understand from our side.
- To take some of the example of combustion design and analysis by both simulation and experimental result based methods.
- Needs also give some hands on training in combustion related numerical problems.
- More problem solving.
- Some level of problem solving involving software such as ANSY, to have an overall idea.
- Some advanced combustion topics can be added.
- Already improved.
- This course could be improved by having more hands on sessions and software workshop.
- Including tutorial problems.
- Research centre visit, practical approach – 30% would help to understand.
- If tutorial type sessions are arranged, then it will further improve the course benefits.

- Accommodation and food could have been arranged in the same hall, hard copy of a good book could have team given.
- More problem solving.
-

7. What did you most appreciate/enjoy/think was best about the course?

- The visual aids used during the course.
- Lab visits and the break.
- All the instructors are highly knowledgeable in their areas.
- Course materials is very useful.
- The lectures by Prof. S. Aggarwal and Dr. Ashok De.
- IITK has done this course in excellent manner.
- Lab visit.
- I know the depth about combustion, so it is most enjoyable thing for me.
- The instructors.
- Getting whole concept about going on research in combustion field.
- Admired by the personality of Suresh Agarwal sir, In spite of his age factor he stood from 9:00 am to 4:00 pm all along and made a beautiful and in depth presentation.
- To focus on fundamentals and explanation by simulation and experimental results.
- Best course I have joined
- Structure of course.
- The environment was good for a better understanding.
- The course is delivered in proper way which was very interesting & very easy to understand.
- Course pattern.
- The stay and pleasant atmosphere at the campus.
- Clear explanation of fundamental concepts.
- Scholar’s expertise plus campus atmosphere.
- Lecture sessions and lab visits.
- Prof. Suresh Aggarwal’s enthusiasm in including recent data was highly motivating.
- Interaction with course coordinators, open discussion course materials.

OUTCOME

- This course presented participants with knowledge of fluid mechanics and thermodynamics on how to move to an integrated understanding of combustion and their potential applications and challenges in the development of modern combustor systems for the transportation, power-generation and other industrial applications. Appreciate the role of fluid mechanics and thermodynamics in combustion
- This course gave better knowledge of chemical kinetics in combustion to all its participants.
- They experienced hands on training on combustion related problems
- Participants got an idea on how to diagnose conditions leading to the different mode of combustion
- The course explained how to optimally select tools for analysis a particular mode of combustion
- After attending the course participants had higher appreciation for the role of combustion in:
  - designing reacting flow systems (combustors) for improved performance
  - designing high-performance reacting systems from end-user's perspective

Organizer's Report

Report on TEQIP Course on "Combustion: Fundamentals and Combustion" held between 16th to 26nd Nov 2016 at IME, Conference Room, IIT Kanpur

Course Co-ordinator:

Dr. Ashoke De
Associate Professor
Department of Aerospace Engineering
IIT Kanpur

Overview

Combustion is still the world's most important and most widely used energy conversion technology. Potential environmental damage and limited resources of fossil fuels require more intensive efforts to better understand the underlying combustion processes. The fundamental knowledge of combustion is expected to improve the design of the industrial combustion systems by enhancing the flame stability, improving the combustion efficiency, and reduction in pollutant formation. The short course is expected to cover fundamental understanding of this multi-scale, multi-physics problem, i.e. combustion and their potential applications and challenges in the development of modern combustor systems for the transportation, power-generation and other industrial applications.

Objectives

This course will enable engineers and researchers with knowledge of fluid mechanics and thermodynamics to move to an integrated understanding of fundamental aspects of combustion, especially in the field of single phase and multi-phase combustion. It will present primarily the fundamental aspects and recent progress in the fields of combustion, while establishing important connections with the underlying fluid-mechanics and thermodynamics. Further, it will present and explore multiple examples of combustion in real life applications.

Course Details:

The proposed course has covered the following topics:

1. **Thermochemistry: Thermodynamics of a Reacting Mixtures**
   - Introduction to combustion, flames and fuels
   - Thermodynamic or state properties of a reacting mixture
   - Concept of equilibrium
   - First law of thermodynamics, internal energy, work, enthalpy
   - Heat of combustion, heating value of fuel, adiabatic flame temperature
   - Chemical equilibrium, Second law of thermodynamics, entropy, Gibbs free energy,

equilibrium constant
- Calculation of equilibrium composition and temperature, use of chemical equilibrium software.

2. **Chemical Kinetics and Reaction Mechanisms**
   - Introduction, various time scales, Damköhler number
   - Law of mass action, reaction rates for single reaction and multiple reactions
   - Forward and backward reactions, state steady approximation, equilibrium constants
   - Elementary and global reactions, chain reactions
   - Reaction mechanisms for the oxidation of hydrogen CO, and hydrocarbon fuels
   - Mechanisms for NOx and soot formation

3. **Governing Equations for Chemically Reacting Flows**
   - Convective and diffusive flux of mass, momentum, and energy
   - Transport properties for a reacting mixture; diffusivity, thermal conductively, viscosity
   - Molecular models for transport properties
   - Species mass conservation and mixture mass conservation equations
   - Momentum conservation equations
   - Energy conservation equation (various forms)
   - Governing equations for one-dimensional flow and axisymmetric jet flow
   - Lewis number and Schmidt number, Shvab-Zeldovich form of the energy equation

4. **Simplified Reacting Systems**
   - Ignition/Combustion in a constant pressure system and a constant volume system
   - Combustion in a perfectly stirred reactor (PSR), and a plug flow reactor (PFR)
   - Use of software package (CHEMKIN, etc.) to analyze above systems

5. **Laminar Premixed Flames**
   - Nonpremixed, premixed and partially premixed flames
   - Premixed flame speed, flame thickness, flame structure
   - Dimensional (or scale) analysis of a premixed flame
   - Simplified analysis of a premixed flame, effect of various parameters (pressure, temperature, equivalence ratio, fuel type, additives, etc.) on flame speed and thickness
   - Flame extinction
   - Detailed analysis of a premixed flame; Use of software package (CHEMKIN, etc.)

6. **Laminar Non-Premixed (Diffusion) Flames**
   - Laminar Jet: flow characteristics, governing equations
   - Qualitative analysis of a reacting jet, flame sheet approximation, flame shape and flame length, effects of various parameters (nozzle diameter, velocity, diffusivity, fuel type, etc.) flame length, methods for controlling the flame length
   - Mixture fraction, concept of conserved scalar, governing (conservation) equation for the conserved scalar, state relationship, relevance of turbulent diffusion flames

- Opposed flow diffusion flames, flame extinction
- Jet flame lift-off and blowout
- Pollutants formation in flames

7. **Spray Combustion**
   - Droplet and spray modelling, Eulerian and Langrangian approaches
   - Droplet evaporation and combustion
   - Governing equations for two-phase flows
   - Spray Combustion

Contribution:

This course will enable engineers and researchers with knowledge of fluid mechanics and thermodynamics to move to an integrated understanding of fundamental aspects of combustion, especially in the field of single phase and multi-phase combustion. With this in mind, we drew on the expertise available within IITK, India and the U.S.A to deliver a course which would enable participants to learn from the best domain experts in their fields. We had a total of 40 hours of lectures and an additional 6 hours of hands-on laboratory sessions.

International Faculty:

Prof. Suresh Aggarwal is a Professor and Director of Flow and Combustion Simulation Laboratory at University of Illinois, Chicago, USA. His research interests include theory, simulations and experiments on laminar and turbulent combustion, emission, spray combustion and combustion instabilities.

IIT Kanpur Faculty:

Prof. Abhijit Kushari is a professor of Aerospace Engineering at Indian Institute of Technology, Kanpur. His research interests are rocket and gas turbine propulsion, instrumentation in combustion and fluid mechanics, liquid atomization and liquid combustion, active flow control, combustion instability, experimental fluid mechanics, high speed flows.

Dr. Ashoke De is an Associate professor of Aerospace Engineering at Indian Institute of Technology, Kanpur. His research interests are CFD, turbulent combustion, turbulent flows in gas turbines, hydrogen combustion, stochastic

PDF based combustion modelling, high speed aerodynamics, high performance computing.

Feedback from the participants:

Out of the 36 participants who registered, 33 of them were present for the course. We had a mix of faculty from private and government aided colleges, faculty from other sister IITs, students (Ph.D/M.Tech) from all over the country, and some participants from the Govt. Research Organizations and Private Industry.

The course was very well received and all sessions were very interactive. The participants were highly appreciative of how the course was structured from start to finish and of how the learnings in classroom teachings translated to hands-on experimental sessions. Many of the participants had never before done any such experiments as they did during the course.

Overall, we believe that this was a very successful course. It was the first course of its kind in India (fundamentals in nature), and we hope that this motivated interest in the field of combustion which can translate to renewed interest and focus on fundamental research and activity to strengthen the manufacturing enterprise in the country.

Key take-away from the course for the participants

Participating in the course, we hope has enabled participants to:

- Gain knowledge about fundamental mechanisms of combustion
- Appreciate the role of fluid mechanics and thermodynamics in combustion
- Understand chemical kinetics in combustion
- Gain hands on training on combustion related problems
- Diagnose conditions leading to the different mode of combustion
- Optimally select tools for analysis a particular mode of combustion
- Appreciate the role of combustion in:
    - designing reacting flow systems (combustors) for improved performance
    - designing high-performance reacting systems from end-user's perspective

Acknowledgements:

In the end, we sincerely thank the TEQIP team. They made an impeccable arrangement for the program and also took care of all the necessary details (posters, dinners, tags, etc). This workshop would not have been successful without their constant support.