Combustion, a three-day advanced course

Session 1: **Fundamental theory and molecular concepts**
Lecture 1 – Introduction
Lecture 2 – Thermodynamics/Kinetics and turbulence
Lecture 3 – Gas burnout
Lecture 4 – Particle burnout

Session 2: **The macroscopic behaviour of burning gases and particles**
Lecture 5 – Flames and their properties
Lecture 6 – Fixed and fluidized beds
Lecture 7 – The fireplace

Session 3: **Combustion chambers, emissions and practical aspects**
Lecture 8 – Combustion in practice
Lecture 9 – Stuff leaving the combustion chamber
Lecture 10 – Diagnostics based on control system data

Literature: Norbert Roberts, *Turbulent combustion*, Cambridge University 2004, 321 pages.
The book is available from several web-based bookstores, hard-copy as well as pdf-format, and is easiest found through a search for its ISBN 0-511-01927-0.

Turbulence itself is not covered in the course book so I would suggest you download the paper by Bjørn Magnussen that was [presented in Lisbon 2005](#).

Bergdala 2016-12-23
Björn Zethræus

Contents

Session 1

The first session is to introduce some basic concepts of combustion, concepts and processes that are common to all types of combustion processes regardless of fuel and technology.

The phenomenon of combustion has been an object of study and of speculation since ancient time – being an element already for the "old Greek".

Common understanding as of today:
- Combustion is generally understood to be a luminous, heat-releasing, non-reversible and rather slow oxidation reaction. It is also generally undestood that the process shall be self-sustained so that once it has started it propagates by itself without any external aid until either the fuel or the oxidiser is exhausted.
- The propagation is usually a slow process and especially so for solid and liquid fuels. Typically, the flame speed is ≈ 1 cm/s for flames spreading on solid fuels and < 0.5 m/s for premixed fuel-and-air gases burning at rest or moving freely as turbulence balls in combustion chambers. In turbulent conditions, the flame propagation speed may be increased up to 100 m/s. If coupled to a pressure-wave, the flame front propagation may change from a deflagration front across which the pressure is (almost) constant to a detonation front, and then the propagation speed may become as high as 1000 m/s.

Before chemistry became the science it is today fire, and hence the whole concept of combustion, was often attributed to deieties and most mythologies will have legends concerning how fire was brought from the gods to the humans. But succesively the pehnomenon came into being better and better explained:

Lecture 1: A bit of history

In 1663 did Robert Boyle find that combustion required not only fuel but also air. Approximately at the same time, 1697, did Georg Ernst Stahl suggest that fire was a substance ("phlogiston"), the visible component of the flames, that was released from combustibles as they reacted with air. At the same time was also released another substance, "caloric", the heat. Caloric was introduced by Antoine Lavoisier in 1777 and at the same time he also suggested that the total mass had to be conserved as a chemical reaction occurred in a confined environment.
- Phlogiston was a material fluid present in fuels (wood, coal, metals and living beings), that escaped from them when bodies are heated to burn.
- Air was considered a phlogiston absorber, needed to let it escape from fuels. If air was trapped inside a bell, fuels could not release all their phlogiston because the air could not hold it. Plants slowly take phlogiston from the air or sunshine, and may suddenly release it if burned.
- Phlogiston was conserved; e.g. animals exhale phlogiston by the mouth, it is stored in the air and in plants, and returns to animals when they eat plants, or to air if plants are burnt. The phlogiston released by metals when rusting could be fed-back from phlogiston-containing substances (metals are obtained from their ores by calcination with wood or coal). Water dissolves phlogiston, but does not destroy it.

- Phlogiston can be quantified by the weight difference before and after burning the fuel.

A decade later, 1799, did another French chemist, Joseph Proust, suggest that chemical reactions in general, and combustion too, would always proceed to consume substance *A* in a fixed proportion to substance *B*. If any of the substances is supplied in excess, the excessive material will be left unaffected, un-reacted, after the reaction. This concept was further refined by John Dalton from England in 1803 who suggested that the proportions had to be integer numbers and by Jöns J. Berzelius who measured the reacting masses with a high accuracy during the second half of the 1820's.

Combustion had now been de-mystified and reduced to a chemical reaction among others but it still had its oddities. In 1815 Sir Humphry Davy discovered that a flame could not pass through a wire mesh in case the mesh was too fine. This quenching effect is the fundamental phenomenon behind the miner's safety lamp. Later, in 1855, Robert Bunsen in Heidelberg measured the temperatures and the burning velocity in premixed flames. In 1860 did Bunsen put a prism beside the Bunsen flame and discovered that the spectrum emitted from a flame was not continuous but exhibited distinct lines. Adding different substances to the flame altered these lines in that more lines were added to the spectrum. This observation was one part of the atom model with its electron orbitals that was suggested by Niels Bohr in 1913.

By the late 1800's did the development of thermochemical theories and models bear fruit in that Louis-Camille Mallard and Henry Louis Le Châtelier proposed an internal flame structure in 1883. By 1900 David L. Chapman and Emile Jouguet found that detonations fronts propagate at a velocity equal to the speed of sound and by 1943 did Yakov B. Zeldovich describe the condition for such fronts more in detail. This ignition theory was then based on a non-uniform temperature, an extension of the uniform-temperature theory of ignition suggested by Nikolay Semynov in 1928. Otherwise, Zeldovich might perhaps be more well-known today for his theory on the formation of nitrogen oxide through a thermal mechanism, proposed 1943.

While the premixed flames had been thoroughly studied ever since the mid 1800's it took until 1928 before Burke and Schumann managed to present a theoretical solution to describe the shape and structure of non-premixed, diffusion flames. Once the first break-through concerning the couplings between thermal and diffusive modelling the development continued and during the 1940's through to the 70's several analyses were published including descriptions of instabilities in two-dimensional flames.

In 1953 did Theodore von Kármán give a lecture in Maryland where he introduced a problem area he called "aerothermochemistry" as the problem of fluid dynamics connected and interacting with heat releasing chemical reactions. This triggered research in this cross-disciplinary area and since the 1970 has the development of commercial and non-commercial computer codes to treat combustion as coupled to heat transfer and fluid-dynamics in complex geometries accelerated.

Lecture 2: Lengths and times in combustion

25 slides

1-4	Setting up a simple model gas for further referencing
5-9	Estimating kinetically controlled rates
10-23	Estimating transport controlled rates using EDC
24-25	Comparison

Lecture 3: Flames, flame speeds, flame structures

34 slides

1-6	Estimating the laminar flame speed
7-10	About the laminar flame speed
11-14	Deflagrations and detonations
15-18	Explosion limits
19	Concentration measures
20-26	Turbulent flame speed
27-35	Flame structures and triple-flames

Lecture 4: Particle combustion

21 slides

1-5	Drying – Devol – Gas combustion – Solid-phase burnout
6-9	Pulverized-fuel flame speed
10-14	Flame propagation in fixed beds
15-20	Particle burnout times
21	Comparison droplets vs. solid particles

Session 2

Session 2 is to introduce the combustion process as such. Combustion can occur in different settings; it can be homogeneous or heterogeneous and it can be transport controlled or it can be kinetically controlled. So using some of the fundamental concepts from session 1 this session aims at describing some of the practical aspects of combustion. So in this lecture the scale shifts from the molecular level phenomena in lecture 1 to cover macroscopic phenomena. Ultimately, in lecture 7, this will lead up to demands set by the combustion process and how they affect the combustion chamber design.

Lecture 5: Flame length, ignition, stability

50 slides

1-3	Molecular and turbulent diffusion
4-9	Free-jet approach to flame length estimates
10-17	Ignition and the radical pool
18-22	Semenov homogeneous ignition
23-24	Frank-Kamenetski non-homogeneous ignition
25-27	Ignition energy
28-34	Ignition and flame propagation in pulverized fuel flames
35-39	Flame stability and -speed with pulverized fuels
40-50	Flame stabilisation in practice

Lecture 6: Combustion in beds

21 slides

1-6	Erguns' equation
7-9	Cross-sectional combustion intensity limit in fixed beds
10-21	The fluidisation curve – *Fixed bed 10, Bubbling bed 11-15, Circulating bed 17-21*

Lecture 7: Combustion in the combustion chamber

30 slides

1-4	Three steps along a flame
5	Nitrogen oxides
6-7	The combustion chamber and the over-all burnout
8-15	Fuel nitrogen conversion
16-19	The combustion chamber and staged combustion
20-27	Different combustion technologies
28	Over-all comparison of technologies (1)
29-32	General conclusions about limitations and over-all residence times
33	Over-all comparison of technologies (2)

Session 3

Session 3 is to conclude the course and to "tie up the sack". The perspective now shifts from inside the combustion chamber to outside.

Lecture 8: Process control in the combustion chamber

40 slides

1-7	Repeating the fundamental conditions
8-11	Setting up the reference case
12	Secondary air introduced too soon
13	Secondary air introduced too late
14	Secondary air flow too big
15	Secondary air flow too small
16	Thermal load too big
17	Thermal load too small
18	Summary
19-20	Primary-/secondary air control strategy
21	Diagnostics based on the control strategy
22-27	Reasonably good, 12 MW hot-water boiler, gas mixing behaviour
28-30	Reasonably good, 12 MW hot-water boiler, load behaviour
31-32	Reasonably good, 45 MW wood-powder fired boiler behaviour
33-36	Grate-fired boiler with low-load mixing problems
37-40	High-load problems in an 8 MW grate-fired boiler

Lecture 9: Stuff leaving the combustion chamber

27 slides

1	Emission categories
2-4	Bottom-ash
5	Fly ash
6-8	Other particles
9	Unburnt gases from the primary zone
10	Unburnt gases from elutriated particles
11	Other gases
12-15	CO and THC
16	Emissions and fuel
17	IED
18-20	Sulphur additives
21-22	The combustion process …
23-25	Another categorization of gas-phase emissions
26-27	Strategy to improve environmental performance

Lecture 10: Using operational data for diagnostics

38 slides

1-4	Basics: the "three T"
5-8	Gas residence time
9-12	Gas temperature
13-15	Gas mixing intensity
17-29	Three different cases with wood fuel
30	Summary comparison of the three cases
31-38	Another way: Regression analysis (Anna Fredriksson)