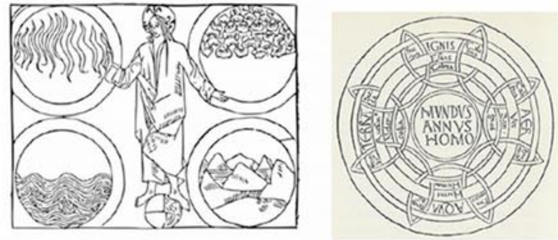
Combustion physics

How a Master's project in combustion diagnostics led to a new division at the Department of Physics and together with other divisions at LTH formed the Thulin Laboratory.

Antoine Lavoisier (1743-1794)
and his wife Marie Anne Pierrette Paulze (1758-1836).



The four elements proposed by the ancient Greeks, some of which remain to be characterized in detail. What is the composition of the interior of our planet? Why does the earth have an atmosphere? When was water formed on earth? Why does combustion take place? What exactly is fire? We only have partial answers to these questions.

According to the ancient Greek philosophers, fire was one of the four elements that, together with earth, water and air, made up the universe. The notion of fire as a basic element persisted, and during the 18th century was known as phlogiston.

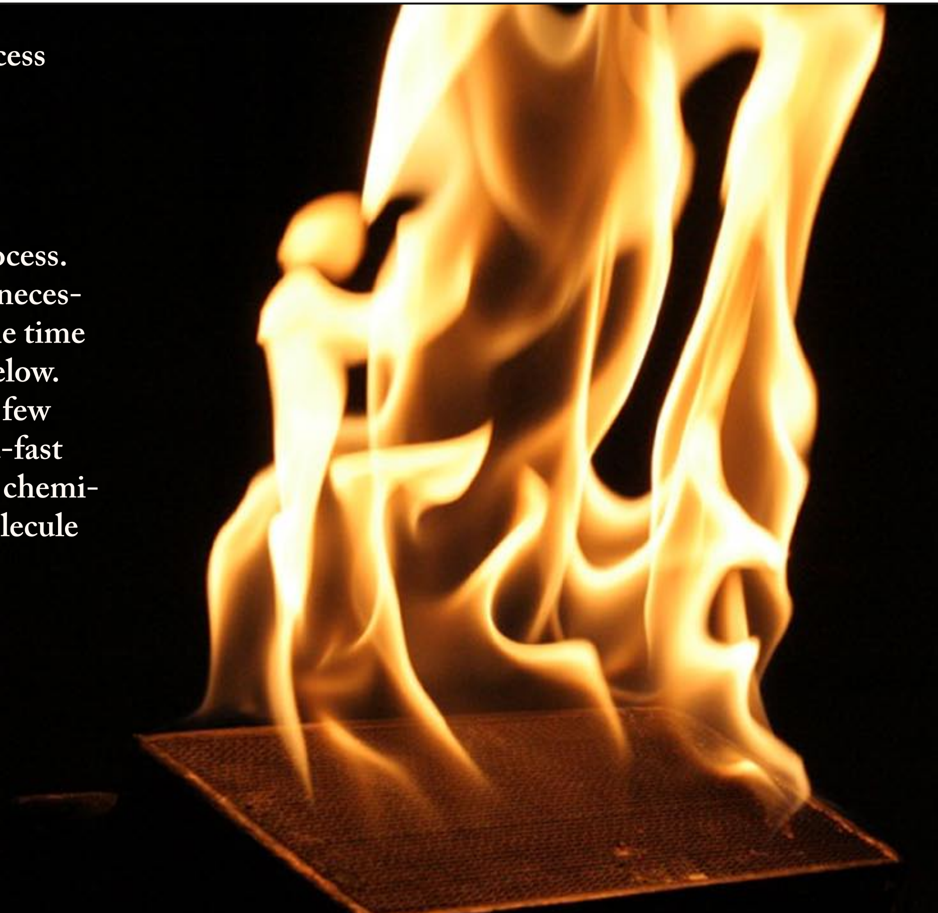
The French chemist Antoine Lavoisier and his wife and collaborator Marie Anne Pierrette Paulze carried out accurate experiments in which they measured the total weight of fuel and air, and found it to be the same as the total weight of the ash and gases formed by combustion. They therefore came to the conclusion that combustion was a chemical reaction, and the notion of phlogiston was disproved.

Combustion

Combustion may appear to be a simple process when expressed as below:

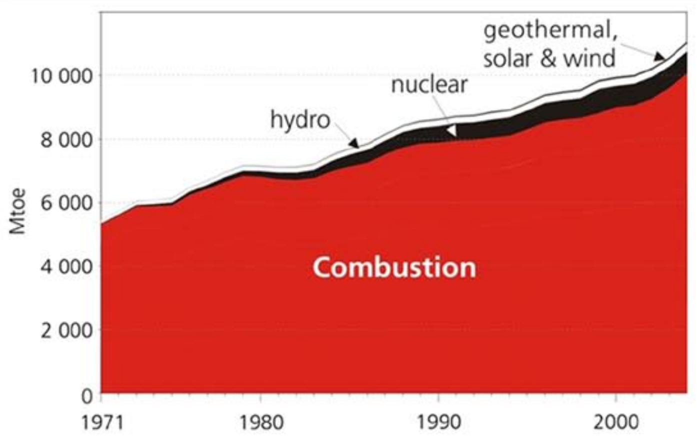
Fuel + oxygen → carbon dioxide + water + energy

In reality, it is a much more complicated process. In order to study combustion in detail, it is necessary to be able to make measurements on the time scale of 10^{-15} seconds (femtoseconds) and below. It has only become possible during the past few decades, thanks to the development of ultra-fast detection systems, to study the hundreds of chemical reactions taking place when a simple molecule like methane, CH_4, is combusted.



Diffusion flame.

The global energy supply

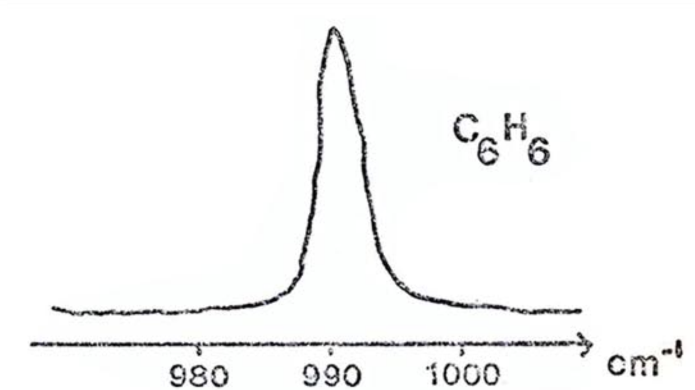


Development of the total global energy production since 1971.

Today, over 80% of global energy is supplied by combustion. Combustion affects most aspects of our daily life, for example, heating, transport (by road, rail and air) and the incineration of waste.

The aim of combustion research is to optimize the combustion process so as to minimize the amount of fuel required and the release of CO_2 and other by-products.

Combustion research



A figure from Aldén's Master's project, which was the first step towards combustion physics in Lund, showing a coherent anti-Stokes Raman spectroscopy (CARS) spectrum of benzene, recorded at 1.30 a.m. on 23rd December 1977. This turned out to be an important part of his study.

Combustion takes place at high temperatures and pressures, and it is thus important to understand the interaction between chemistry and turbulent flow, and how pressure affects the process. The questions that need to be answered are: What should we measure and simulate? How can we make such measurements? How can we simulate the process?

Combustion research at Lund is based on a Master's project carried out by Marcus Aldén, a former student at Chalmers University of Technology, under the supervision of Sune Svanberg and Thure Högberg (Volvo). Aldén performed non-intrusive measurements using lasers to study various combustion processes.

Rapid expansion

Marcus Aldén

The combustion group expanded its activities into new areas, and the Division for Combustion Physics was founded in 1991. A professorship in laser-based combustion diagnostics was awarded to Marcus Aldén the same year.

Combustion research in Lund is characterized by collaboration between several disciplines. For example, the Lund University Combustion Centre was formed, and has had the status of a European Large Scale Facility (LSF).

The Enoch Thulin Laboratory

The Enoch Thulin Laboratory, inaugurated in 2001.

Combustion research at Lund expanded rapidly from the very beginning. Heavy equipment, including a new high-pressure combustion test rig, the only one of its kind, required a lab of its own.

The Enoch Thulin Laboratory was built at the Department of Physics and was inaugurated in 2001. This allowed most of the more fundamental combustion research in Lund to be collected under one roof, enabling closer and deeper collaboration between different departments.

The laboratory is named after Enoch Thulin (1881 - 1919), a pioneer aviator who obtained his PhD at Lund University.

Why laser diagnostics?

Important developments in computing power and advanced diagnostics at the turn of the century made it possible to study the combustion process in detail. Non-intrusive optical diagnostics using lasers became possible, allowing studies of the short-lived compounds that are formed during combustion under specific conditions.

It also became possible to measure temperature, flow and velocity, as well as concentrations, including soot, and particle size, with high temporal and spatial resolution. Marcus Aldén's first PhD student, Per-Erik Bengtsson, is now a professor at the division and responsible for research in a number of areas of combustion diagnostics.

Two photographs of a laminar Bunsen burner flame, without a probe (left) and with a thermo-element inserted into the flame (right) to measure the temperature at a specific point. Insertion of the probe leads to changes in the flow, causing a lowering of the temperature and changes in the chemical reactions taking place. This can be avoided by using non-intrusive laser diagnostics.

Laser-induced fluorescence – LIF

Laser radiation has many properties that make it suitable for studying combustion without interfering with the process.

In laser-induced fluorescence (LIF), the wavelength of the laser light is chosen such that it matches the difference in energy between two levels in the molecule being studied.

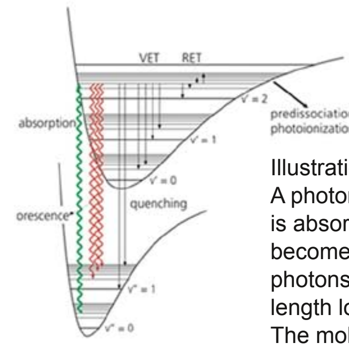
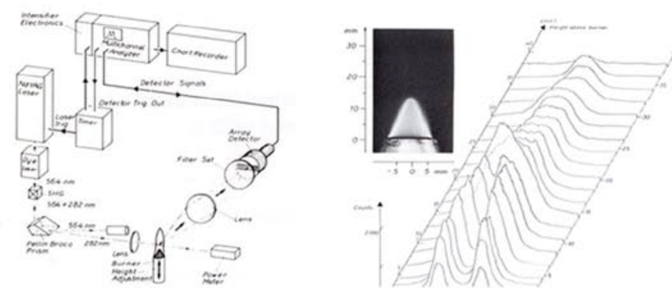


Illustration of LIF and its decay mechanisms. A photon from the laser (shown in green) is absorbed by the molecule causing it to become excited. The molecule then emits photons (shown in red), often with a wavelength longer than that of the laser light. The molecule thus returns to a lower energy level and the energy emitted is seen as fluorescence.



Spatially resolved fluorescence of OH in a flame and the distribution of OH radicals.

Laser-induced incandescence

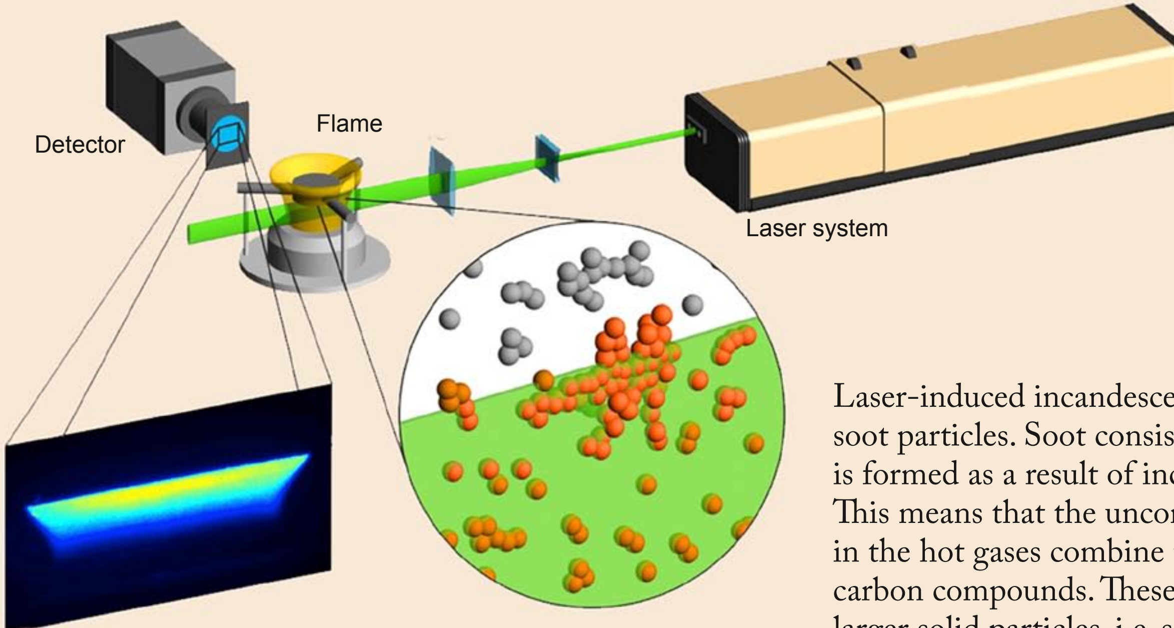
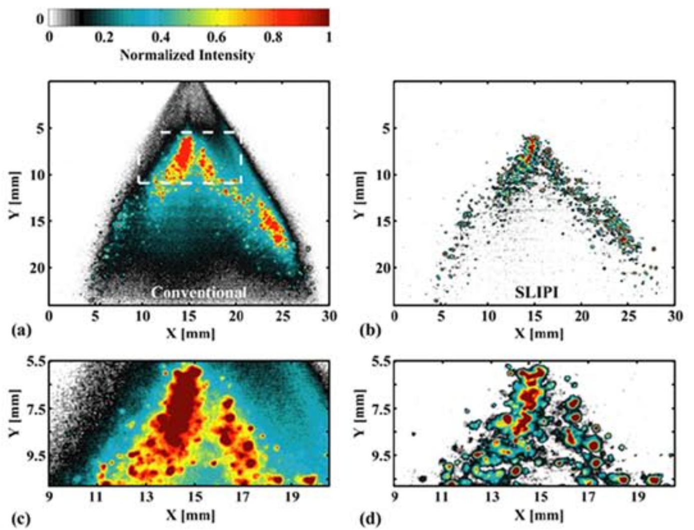


Illustration of the measurement of soot concentration (volume fraction) in a laboratory flame.

Laser-induced incandescence (LII) is used to study soot particles. Soot consists mostly of carbon, and is formed as a result of incomplete combustion. This means that the uncombusted hydrocarbons in the hot gases combine to form ring-shaped carbon compounds. These then combine to form larger solid particles, i.e. soot.

LII is used to detect the light emitted by soot particles when they are heated to a temperature of about 3 500 °C by laser light. The signal provides a measure of the soot concentration in the region being studied, but can also provide information on particle size.

Other laser techniques



Images of sprays used, for example, in diesel engines, taken with conventional laser photography (a) and with SLIPI (b), which removes unwanted signals, such as the dark area surrounding the droplets in the left-hand figure.

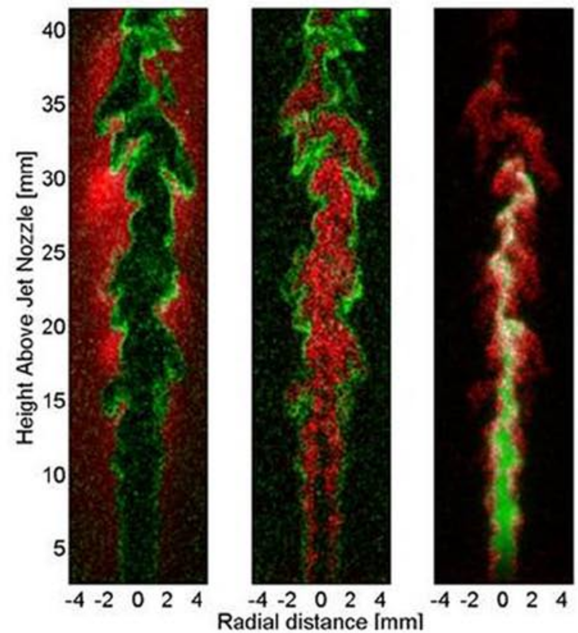
New laser techniques have been developed at the Division of Combustion Physics, examples of which are CARS, in which the gas temperature can be measured accurately, and polarization spectroscopy, with which extremely small amounts of a compound can be detected in a flame.

Rayleigh scattering is used to measure temperature, structured laser illumination planar imaging (SLIPI) to study sprays and dense clouds of droplets, thermographic phosphors for measuring the surface temperature, and particle image velocimetry (PIV) for measuring flows and velocities in gas flows.

Turbulence

High-speed diagnostics is used to study the development of turbulent structures. As turbulence is a three-dimensional phenomenon, 3D measurements with high temporal resolution are needed to understand turbulent flames.

A 3D system consists of four Nd:YAG lasers and a high-speed camera. Each laser generates two laser pulses within a short time interval, and a total of eight laser pulses are therefore emitted in each pulse train. Using four separate lasers allows different combustion products to be measured simultaneously.



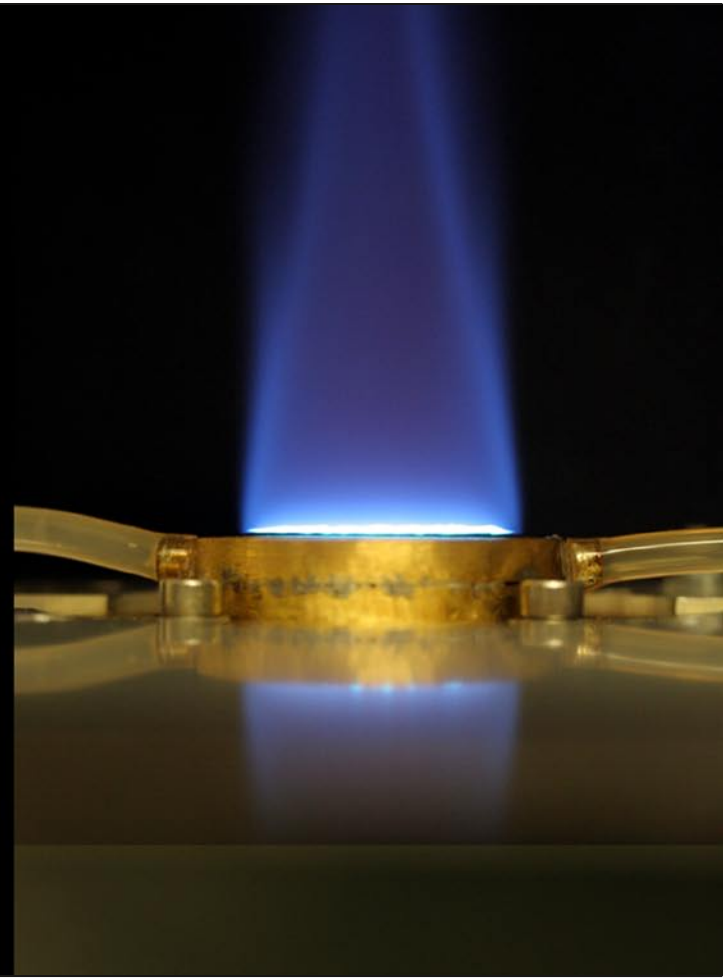
This figure shows LIF measurements of OH (warm product), CH (flame edge), CH_2O (cool zone) and traces of uncombusted fuel (cold zone) in a turbulent jet flame. Each image contains two products. Left: OH (red) and CH (green), Middle: CH_2O (red) and CH (green), Right: CH_2O (red) and fuel (green).

Chemical kinetics

In terms of chemical kinetics, combustion is an incredibly fast series of chemical reactions in which both heat and light are generated.

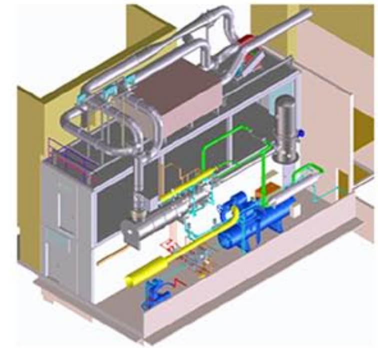
Within chemical combustion research, chemical models, both theoretical and practical, are being developed that describe combustion in, for example, flames and engines. An important part of this research is the experimental determination of the molecular composition of flames.

Scientists at Lund are extremely skilled in the areas of combustion chemistry and laser diagnostics in flames, providing unique possibilities to study the combustion process. Alexander Konnov from St. Petersburg is responsible for this field of combustion research.

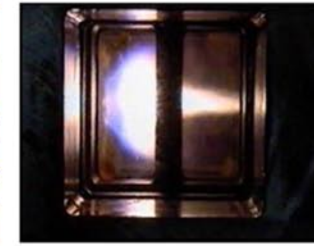


The high-pressure combustion test rig

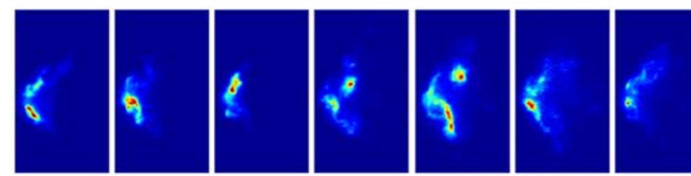
The high-pressure combustion test rig at the Division of Combustion Physics gives scientists in Lund the possibility to study combustion at high pressures and flows that are similar to those found in gas turbines and aircraft engines. The combination of this test rig and advanced optical/laser-based techniques is unique, and benefits both industry and society as a whole. The measurements made with this equipment provide insight into the complicated processes taking place in different kinds of combustion.



The high-pressure combustion test rig.



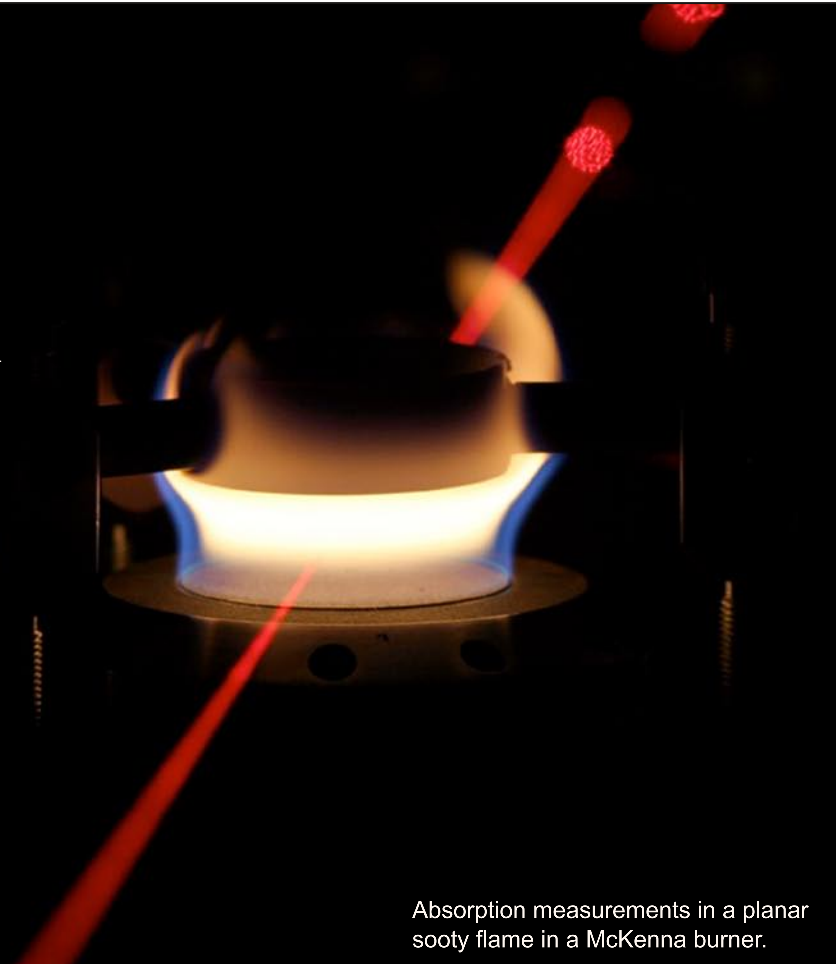
Photograph of a pilot flame in one of the burners tested in the high-pressure combustion rig.



Time series of images of fuel (fuel LIF) from one of the many runs performed using the high-pressure combustion test rig.

The need for more research

Fossil fuels must soon be replaced, and combustion must be made more efficient and environmentally friendly. Renewable fuels must be developed, and diminishing global resources require more energy-efficient equipment. The consequences of acidification and the greenhouse effect have led to political decisions that place higher demands on society. Although the use of fossil fuels is decreasing, our use of biofuels is increasing. This brings with it new challenges. A more sustainable society requires a deeper understanding of combustion and better knowledge concerning the problems involved in the transformation to alternative sources of energy.



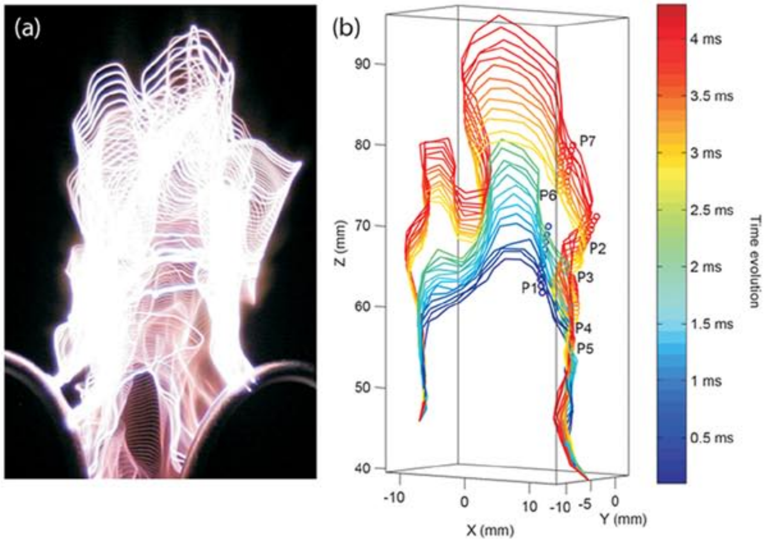
Absorption measurements in a planar sooty flame in a McKenna burner.

Combustion physics today – from ecology …

LUMBO – the Lund University Mobile Biosphere Observatory – is used to study the fauna in the atmosphere, and is one of the new areas of research at the Division of Combustion Physics.

Although much of the research in combustion physics is centred around combustion, the division is also working in a number of other areas where basic knowledge in laser diagnostics, physics and chemistry is important.

A number of methods have been applied for several years to non-reactive gas flows, including the detection of hydrogen peroxide in the sterilization process at Tetra Pak, and optical remote sensing (Lidar) in atmospheric and ecological applications.



(a)
Photograph of a sliding discharge plasma. Like our own eyes, a normal camera cannot discern the discharge as it moves rapidly in the air flow.

(b)
Using two high-speed cameras and mathematical image analysis it is possible to obtain images of the discharge at any instant, providing three-dimensional velocity information. The gas flow in this case was tagged with particles to enable the velocity of the surrounding gas to be measured (P1-P7).

The considerable efforts made in laser diagnostics in combustion have made it possible to branch out into completely new areas.

Examples of these are plasmas, gasification, catalysis and nanometer technology. Within catalysis, for example, the gas around an active catalyst can be studied in real time, providing information not previously obtainable.

In plasmas, molecules can be created in special states and their chemical properties can be studied using laser and optical diagnostics.