# Experiments in Combustion

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## Preamble

The aim of this lecture note is to present state-of-the-art experiments in turbulent combustion. The lecture is restricted to generic gaseous turbulent flames that feature different characteristics important to practical applications. The methods presented here are feasible to study boundary conditions, flow and scalar fields and are based all on interactions between laser light and matter. Basic knowledge of fundamentals such as quantum mechanics, molecular structure and radiation is presumed.

Following a brief introduction, generic target flames from simple to complex are exemplified. This selection of generic configurations, of course, is far from complete. Chapter 3 and 4 introduce to most popular flow and scalar measurement techniques. At the end of each of these two chapters exemplary applications of the methods are presented. Chapter 5 provides an introduction to combined scalar/flow measurements that can significantly improve our understanding of mutual interaction between chemical reactions and turbulent fluid flow. In chapter 6 new developments based on high-repetition-rate imaging are discussed. These diagnostics complement methods at low repetition rate commonly used to generate an understanding by statistical moments and probability density functions. Due to the increasing role of numerical simulation in designing future combustion technologies, the final chapter 7 reviews some aspects of how experimental and numerical results compare.

# 1. Introduction to experimental combustion research

Turbulent combustion is the backbone of primary energy conversion. Although it is desirable that regenerative energy conversion processes such as solar or wind energy gain in their weight, combustion will keep its dominant role in the foreseeable future. This fact and recent public disputes on global change enforce that turbulent combustion processes in their various applications such as electrical power and heat generation, propulsion and mobility must be further improved in terms of efficiency and pollutant emissions.

Different pathways exist to advance combustion technologies. Figure 1.1 highlights the role of experimental methodologies. Experiments may serve either in a **direct** manner to measure key-quantities of a practical combustion process for subsequent improvements or experimental studies serve in an **indirect** way to support a mathematical/numerical model of the combustion process to be designed in future. Figure 1.1 additionally shows that experimental studies can gain from numerical modelling and numerical recipes. This interplay between experiments and numerical simulation will be touched in chapter 7 whereas the impact of numerical procedures on experimental methodologies is due in data post-processing strategies.

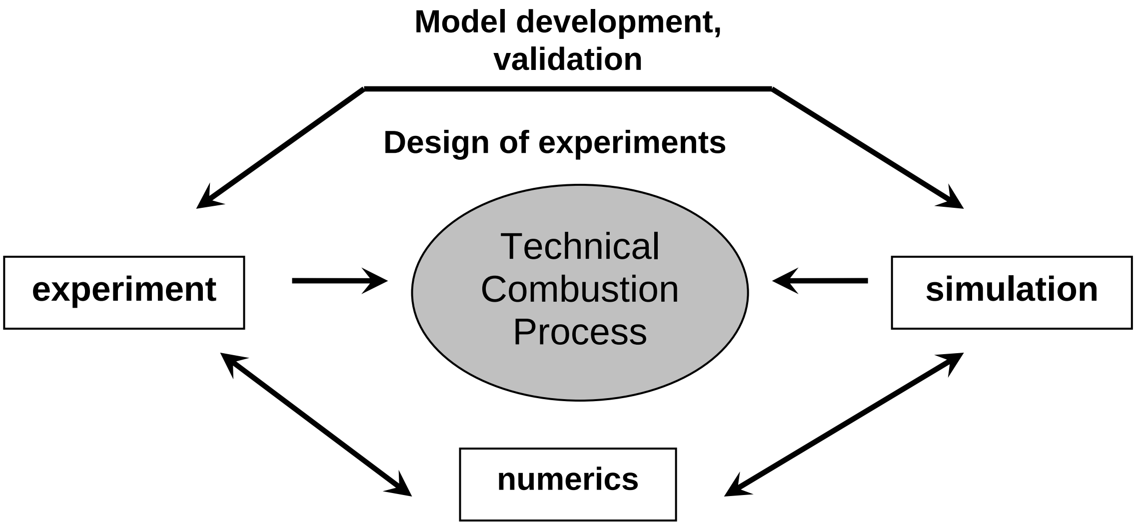


**Figure 1.1**
Mutual interconnections between experiments, numerical simulations/modelling and numerical recipes to improve current combustion technology.

For an experimental investigation of a combustion process two ingredients are necessary: 1) a test rig where the combustion process of interest can be operated and 2) suitable methods for its experimental characterisation. Both aspects will be discussed here to some extent but the discussion is restricted only to **generic, gaseous and continuous combustion processes** that feature some characteristics of general interest and to **laser-optical measuring techniques**. Topics such as coal or spray combustion and IC engines are apparently excluded here.

Optical- and especially laser-based methods are commonly used to study combustion processes in detail. This is attributed to the following features: 1) Optical methods are non- or minimal invasive. 2) Optical techniques can be applied in-situ. The only prerequisite is a suitable optical access. 3) The temporal resolution in comparison to probe-sampling-techniques (gas chromatography, mass spectrometry, etc.) is extremely high. Typical time scales of a practical turbulent combustion process can be resolved. 4) The spatial resolution of optical combustion diagnostics is reasonable. Although it is in general better than intrusive probe-techniques (thermocouple, hot-wire anemometer, etc.) smallest length scales of highly turbulent combustion processes often cannot be resolved. Therefore the sensitivity of the probe-volume size on the result must be examined for each measurand.

To investigate a turbulent combustion process in detail many different quantities are of interest. These quantities of interest can be divided into flow field quantities, scalar field quantities and inflow/boundary conditions.

A turbulent flow field is characterised by its mean and rms-values (root mean square = second statistical moment) of all three velocity components. Higher moments than the second may be in special cases of some interest but impact of experimental noise and other experimental limitations on precision and accuracy are not well studied. In addition to this pointwise information on mean and rms-values some information on length scales such as integral or Kolmogorov length scales or elements of the rate-of-strain and rate-of-vorticity tensor is important. In chapter 3 and 5 it is discussed how laser Doppler velocimetry (LDV) and particle imaging velocimetry can be used to measure these key-quantities of a turbulent flow under chemically reactive conditions.

The scalar field of a combustion process contains the distribution of the temperature, chemical species concentrations and quantities derived from temperatures and/or concentrations. Prominent examples for the latter one are the mixture fraction or scalar dissipation rate in non- and partially-premixed flames or the reaction progress in premixed flames. Linear as well as non-linear spectroscopic methods are widely used to precisely and accurately measure these various key-quantities of the scalar field. However, as quantification in many circumstances is difficult some of these spectroscopic techniques are often used in a qualitative manner only. For example relative distributions of flame-generated radicals such as hydroxyl (OH) serve to divide unburned from burnt regions. In chapter 4 different spectroscopic methods such as laser-induced fluorescence (LIF), Raman/Rayleigh spectroscopy and coherent anti-Stokes Raman spectroscopy (CARS) are discussed along with exemplary applications.

Turbulent combustion is complicated due to the fact that chemical kinetics and turbulent fluid flow mutually interact with each other. More insights into this mutual interplay can therefore be gained from simultaneous flow and scalar field measurements. In chapter 5 combinations of PIV/PLIF and LDV/PLIF show that these simultaneously applied diagnostics allow to switch the point of view from a laboratory to a flame-fixed coordinate system. Averaging and wash-out due to intermittency inherent to turbulent flames is thereby avoided. Furthermore, statistics conditioned on the intermittent flame front becomes feasible.

Boundary and inlet conditions determine many features of turbulent flames. Therefore they need to be recorded and controlled thoroughly. Dependent on the type of process examined, not only inlet profiles at the nozzle exit but profiles inside the nozzle must be known. In case of enclosed combustion, transfer processes (heat, mass, momentum) to the wall should be studied as well. In chapter 2, where examples of optically accessible combustion processes are shown, leadoff approaches are briefly discussed to gain insight into processes inside nozzles. Additionally a first attempt is presented to measure the heat transfer from the gas phase to solid walls.

Laser diagnostics discussed in chapters 3 to 5 are operated in general at rather low repetition rates. In consequence the samples are statistically uncorrelated. To derive reliable statistics