Special fields of application of the light-sheet technique are instantaneous measurements of turbulent flames (see Chapters 12-14) with short light pulses (high temporal resolution). Figure 2.7 shows two-dimensional laser light sheet measurements (OH-LIF) in an Otto test-engine (Becker et al. 1991), which clearly show the turbulent nature of the combustion.

If fluorescent molecules (NO_2, NO, CO, acetone, acetaldehyde) are added to the fuel (or air), additional information about regions with or without fuel, temperatures, etc. can be obtained (e. g., Paul et al. 1990; Tait and Greenhalgh 1992; Lozano et al. 1992; Bazil and Stepowski 1995, Wolfrum 1998).

Usually, these LIF measurements are qualitative in nature, because a calibration of concentration measurements is very difficult due to collisional quenching. Unlike Raman or Rayleigh, the lifetime of the excited state in an LIF experiment is relatively long, (nanoseconds or even microseconds). During this "long time", the excited molecule collides with other molecules. Most of the excited molecules lose energy due to collisions with other molecules (called *quenching*) instead of radiation (see, e. g., Wolfrum 1986). This radiationless loss of energy can not be ignored and has to be accounted for if one is to accomplish quantitative LIF. Thus, a lot of calibration data has to be provided before a quantitative evaluation.

Nevertheless, quantitative measurements can be done in some cases, as demonstrated in Fig. 2.8. Shown are absolute concentrations of OH and NO, and relative concentrations of CH in a premixed laminar flat CH_4-air flame at low pressure. Even the relative concentration profile provides valuable information on the shape and position of the CH-radical profile.

2.4 Temperature Measurements

Thermocouples: Temperature fields can be measured very easily by thermocouples which are pairs of junctions between different metals. A voltage, which is approximately proportional to the temperature difference between the two junctions, is induced (*thermoelectric effect*). Usually different metal combinations are used depending on the temperature range (for instance, platinum/platinum-rhodium or tungsten/tungsten-molybdenum).

The major disadvantage is that the method measures the temperature of the metal-metal junction, which then has to be related to the surrounding gas temperature. Thus, the temperature measured (i. e., that of the metal) can be very different (hundreds of K) from that of the gas. An energy balance will include catalytic reaction at surface of the thermocouple, conductive heat losses via the wires to the (usually) ceramic support, radiation from the wire, and conduction and convection from the gas phase to the wire (see Fristrom 1995). Nevertheless, the method is easy to use and inexpensive and can be applied for qualitative measurements. A comparison between thermocouple measurements and laser-based optical thermometry is presented by Rumminger et al. (1996).

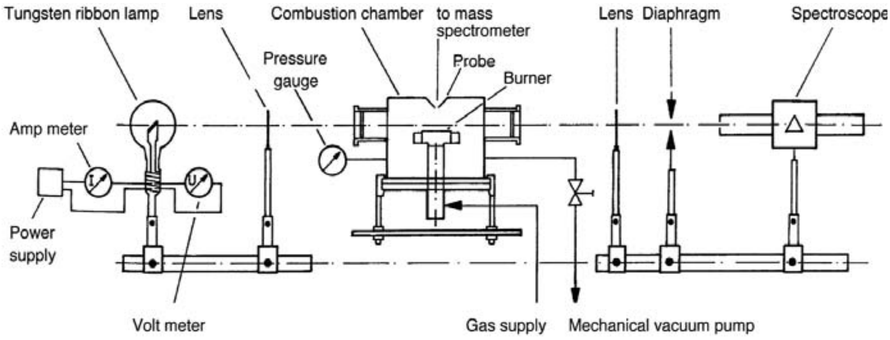

Fig. 2.9. Experimental setup for the measurements of temperatures (Na line reversal) and concentrations (probe sampling, mass spectroscopy, OH absorption) in a laminar flat premixed low pressure flame (Warnatz et al. 1983)

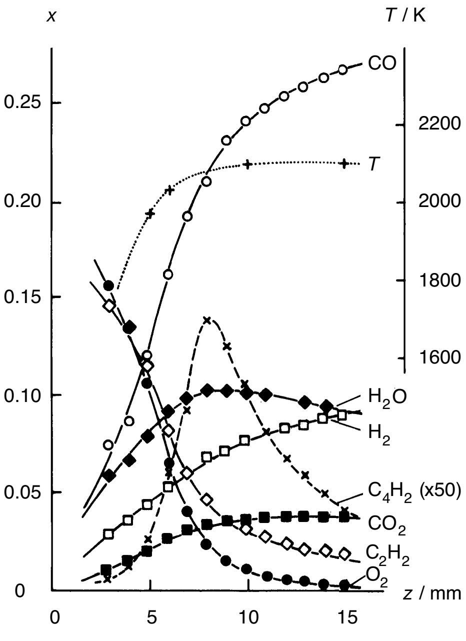

Fig. 2.10. Measured mole fractions (determined using mass spectroscopy) and temperatures (determined using Na line reversal) in a laminar flat premixed low-pressure acetylene/oxygen/argon flame (Warnatz et al. 1983)

Na-Line-Reversal Method: Here sodium-containing compounds are added to the reactants. Sodium atoms can absorb or (at elevated temperatures) radiate yellow light. This emission of added Na in comparison with a *black body* disappears if the Na atoms (or other atoms like Pb or In) have exactly the same temperature as the black body. If the temperature is higher, more light is emitted than absorbed; if the temperature is lower, more light is absorbed than emitted. The advent of diode array detectors greatly improved the detection of adsorption or emission (see Gaydon and Wolfhard 1979). Fig. 2.9 shows an experimental setup, and Fig. 2.10 shows temperature measurements using this method together with concentration measurements, obtained by mass spectroscopy in a rich laminar premixed acetylene-oxygen-argon low-pressure flame.

CARS Spectroscopy: Besides species concentrations, temperatures can be measured by CARS spectroscopy even more accurately. High resolution spectra are compared with simulated spectra which can be derived theoretically from molecular properties of the species under consideration. Temperature and concentration are varied in the simulation until best agreement with measurement.

Advantages are, again, the high spatial (about 1 mm^3) and temporal (about 10 ns) resolution, disadvantages are the high costs and the complicated evaluation of the data, which is mainly due to the nonlinear dependence of the signal on laser intensity and on species concentration (Sick et al. 1991).

Laser-Induced Fluorescence: The selective excitation of different energy levels in molecules (e. g., in OH-radicals) can be used to determine the population distribution of the energy levels. Assuming a Boltzmann distribution, temperatures can be determined (see, e. g., Eckbreth 1996, Thorne 1988). Care has to be taken to account for loss of energy in the laser beam as well as *self adsorption* of the fluorescent light as it emerges from the zone of laser excitation (Rumminger et al. 1996).

In some cases, fluorescent compounds are added to the flow. Seitzmann et al. (1985) added NO and performed LIF thermometry on this molecule. They showed that the NO had negligible effect on the combustion process.

2.5 Pressure Measurements

In unconfined, subsonic-flow flames (such as candles, torches, and flares) the pressure is nearly constant. In confined flows (e. g., as occurs in combustion chambers and furnaces) the pressure is often steady with a slight gradient of pressure maintaining the subsonic flow and accounting for acceleration of the flow. These average pressures are suitably measured with conventional liquid or electronic *manometers*.

Quite often in combustion, the pressure varies in time; examples include piston engines and pulse combustors. These changing pressures are usually measured with wall-mounted *piezoelectric pressure transducers*. These are quartz crystals which change their electrical properties depending on the deformation by pressure variations. The implicit assumption is that the pressure measured at the wall is close to that away from the wall. This assumption is suitable when the time for the pressure changes is long compared to that for a sound wave to traverse the chamber.