Evaporating and combusting droplet temperature measurements using two-color laser-induced fluorescence

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Abstract The paper presents a new technique based on laser-induced fluorescence, allowing droplet temperature measurement of evaporating and combusting droplets to be performed. The liquid spray is seeded with a low concentration of rhodamine B. The fluorescence, induced by the green line of an argon laser, is measured on two separated color bands. It is demonstrated that two color bands can be selected for their strong difference in the temperature sensitivity of the fluorescence quantum yield. The determination of the fluorescence ratio between the fluorescence intensity corresponding to each color band allows the tracer concentration and the droplet size dependencies to be eliminated. The technique was applied on a monodisperse spray: the effect of a thermal impulse on the distribution of the droplet temperature is studied and, the temperature of combusting droplets is investigated.

List of symbols

- C: molecular concentration of the tracer
- D: droplet diameter
- f: piezoceramic frequency
- I₀: incident laser beam intensity
- I_f: fluorescence intensity
- K: fuel thermal conductivity
- K_{opt}: optical constant
- K_{spec}: spectroscopic constant
- L: distance parameter (defined just after the jet break-up)
- r: radial position in the droplet axis system
- R: droplet radius
- R_f: fluorescence ratio
- T: absolute temperature
- T_i: injection temperature
- T_0: reference temperature
- V_i: injection velocity
- V_c: probe volume

Greek symbols

- β: temperature sensitivity coefficient
- e_{f}: extinction coefficient for the fluorescent emission
- e_{i}: extinction coefficient for the laser radiation
- Φ_0: injector aperture diameter
- λ: wavelength

Subscripts

1: first spectral band λ ∈ [525 nm:535 nm]
2: second spectral band λ > 590 nm

1 Introduction

Experimental spray combustion investigations require the development of challenging measurement techniques. Spray combustion concerns automotive engines with direct injection of the fuel in the combustion chamber and also turbojet and rocket engines, where fuel is injected on a droplet form. The thermal characterization of a spray should allow better understanding of the physical phenomena involved in spray combustion and may contribute to saving fuel and to reducing global CO₂ emissions. A spray is a two-phase flow where transport phenomena of heat and mass are strongly related. Heat and mass transfer occur in the wakes generated by the velocity difference between the liquid droplets and its gaseous surrounding. Furthermore, the internal vortex within the droplets contributes to enhancing the heat conduction in the liquid phase. One of the key points which needs to be investigated is the thermal budget between the droplet and its gaseous surrounding in the evaporation and combustion phases. This involves a reliable experimental technique able to measure the droplet temperature. The most usual technique for determining moving droplets temperature is the rainbow refractometry technique (Walker 1976). A laser beam is focused into a droplet and the multiple reflexions within the droplet produce a rainbow figure. The angular position of the rainbow, which may be detected by a photomultiplier (Van Beeck and Riethmuller 1997) or by a CCD array (Van Beeck and Riethmuller 1995), depends on the refractive index of the liquid, related to temperature. The technique is applicable for providing information about the drop size and mean temperature in the case of isothermal droplets. However, the method falls down in the presence of strong temperature gradients within the droplet, for example in the evaporation phase. The other strategy used to determine the droplet temperature is to measure and analyze its
infrared emission (Ravel et al. 1997). The main difficulty is to determine the liquid emissivity, and one of the serious problems is that only the surface temperature is determined, where the influence of the vapor phase radiation must be carefully examined.

Another technique consists in adding fluorescent tracers in the liquid phase. Murray and Melton (1983) demonstrated the potential use of exciplex fluorescence for determining the droplet temperature in hydrocarbon fuel sprays. However, the technique cannot work in a combusting environment. Lavieille et al. (2000) developed a laser-induced fluorescence efficient technique in the liquid phase. A low concentration of a fluorescent organic dye (rhodamine B) is dissolved in the fuel, and the temperature dependence of the fluorescence quantum yield is used to provide a temperature measurement. The technique was demonstrated to be capable of determining the droplet temperature within 1 °C in a monodisperse stream, where size changes due to evaporation were neglected. The major problem was that the fluorescence signal also depended on the droplet volume, which may change in evaporating or combusting sprays.

This paper provides an extension of the laser-induced fluorescence technique which is able to overcome these problems efficiently. Further information about the droplet volume appears necessary in order to determine the temperature even in the case of strong size changes. An alternative strategy is suggested by the work of Copetta and Rogers (1998) and Sakakibara and Adrian (1999): a second fluorescent, whose fluorescence spectral band is well separated from the first one and with a different temperature sensitivity, can be dissolved in the fuel. The ratio of the fluorescence signals measured on the two spectral bands can eliminate the volume dependence. However, one of the difficulties is that the resulting temperature sensitivity depends on the respective dye concentrations in the mixture, so that the concentrations must be well known and maintained constant. The present paper deals with a new laser-induced fluorescence technique based on a ratiometric measurement of fluorescence signals detected on two-color bands of a single fluorescent dye (rhodamine B). The technique allows the laser intensity, dye concentration and drop volume dependence to be eliminated, keeping the sole effect of temperature. Validation of the technique is provided on a monodisperse ethanol droplet stream either in evaporation or combustion. Two droplet sizes were investigated: \( D = 100 \, \mu m \) and \( D = 200 \, \mu m \).

2 Two-color laser-induced fluorescence: principles

2.1 Principles

The basis of the technique is to use the temperature dependence of the fluorescence of an organic dye dissolved in the fuel (ethanol here). Rhodamine B is an adequate tracer, because of its strong temperature sensitivity: this sensitivity is of the order of 3% of fluorescence variation per K. Rhodamine B is highly soluble in ethanol and its fluorescence, centered in the red–orange part of the visible spectrum, is strong. Furthermore, the fluorescence can be easily induced by the green line \( (\lambda = 514.5 \, nm) \) of an argon-ion laser, operating in single-line mode. Lemoine et al. (1999) have shown that the temperature dependence of the fluorescence emission appears mainly in the fluorescence quantum yield, where quenching phenomena are involved. Expressing the fluorescence quantum yield as a function of the temperature gives the fluorescence intensity expression, neglecting Beer’s attenuation of the incident laser beam and the fluorescence re-absorption:

\[
I_f = K_{opt} K_{spec} V_c I_0 e^{-\beta/T}
\]

where \( K_{opt} \) is an optical constant, \( I_0 \) is the incident laser intensity, \( C \) is the molecular concentration of the fluorescent tracer, and \( T \) is the absolute temperature. \( K_{spec} \) and \( \beta \) are two constants depending only on the spectroscopic and physical properties of the fluorescent molecule. The coefficient \( \beta \) can be interpreted as a temperature sensitivity coefficient of the fluorescence intensity. The parameter \( V_c \) is the measuring volume, corresponding to the volume of the droplet excited by the laser radiation, captured by the detection device. The principle of droplet temperature measurement consists in dissolving a very low dye concentration in the fuel and atomizing the liquid into droplets. The fluorescence resulting from the laser excitation is collected by an appropriate optical device. One of the main difficulties in determining the droplet temperature by measuring the fluorescence intensity is the presence of the measuring volume size \( V_c \) in Eq. (1), which may change as the droplet vaporizes. The present paper demonstrates that this drawback can be overcome by using two spectral bands of fluorescence, previously selected for their strong temperature sensitivity difference. The ratio of the fluorescence intensity measured on each color band appears to be independent of the measuring volume \( V_c \). An accurate study of the rhodamine B spectrum has shown that the temperature sensitivity depended considerably on the wavelength. Rhodamine B spectra measured in an ethanolic solution \( (C = 5 \times 10^{-6} \, mol/l) \) are presented in Fig. 1 at three different temperatures: \( T = 24.5 \, ^{\circ}C \), \( T = 36 \, ^{\circ}C \) and \( T = 57 \, ^{\circ}C \). The spectra were realized by a spectrometer with a spectral resolution of

![Fig. 1. Evolution of the rhodamine B fluorescence spectrum as a function of the temperature and distribution of the temperature sensitivity coefficient \( \beta \) as a function of the wavelength](image-url)