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Measurement of the structure coefficient of refractive index fluctuations in a turbulent premixed butane-air flame by means of a laser-based interferometer technique

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ABSTRACT

With a view to measuring the structure coefficient of refractive index fluctuations in a turbulent premixed butane-air flame, a thin laser beam is sent into the flame perpendicular to the flow direction. The laser beam generally undergoes fluctuations of direction, phase, and amplitude. Only the random deflections of the laser beam may be taken into account. After having traversed the flame, the perturbed laser beam enters into an interferometric system. Materials and experimental procedure are described. In the unperturbed interference pattern, the zones only sensitive to fluctuations of the angle-of-arrival of the laser beam are detected. From the random displacements of the central bright fringe, the structure coefficient of refractive index fluctuations in the flame is measured. To prove that the method of measurement is satisfactory, the result obtained is applied for computing the power spectral density of the angle-of-arrival of the laser beam from the formula of correlations of the laser beam deflection angles which we have demonstrated in previous works. This computed power spectral density is compared to that measured from the effective position of the detector. A good agreement is observed between the two results.

1. Introduction

In experimental studies of turbulent flows, the techniques usually applied, notably the cold-wire anemometer technique for measurements of temperature fluctuations and hot-wire anemometer technique for measurements of speed fluctuations, need inevitable probes which are introduced into the flow studied. In spite of improvements which are increasingly made to obtain accurate results from these techniques, the above experimental processes contain drawbacks due to flow perturbations which are created by these probes and cause significant errors in the results obtained. In addition, if the flow speed is high, the response of the hot wire anemometer becomes nonlinear, and this then requires calibrating. For high temperatures, as in the cases of flames and combustion chambers, the cold-wire anemometer technique becomes ineffective. A very convenient technique would be one in which no probe is introduced into the flow. The conventional laser-based diagnostic techniques [1–8] such as laser spectroscopy, Rayleigh scattering, laser tomography, usually applied to study flames and combustion chambers, present this advantage and are increasingly accurate. These methods enable the identification of the species acting in the combustion and the determination of the profile of any parameter in the combustion cycle. But the electrical signals obtained from the detectors used in these techniques cannot be exploited for solving the inverse problem which consists to extracting information about thermal turbulence parameters that characterize the flame turbulence or are essential for the design of engines.

Unlike the conventional diagnostic methods, the laser-based diagnostic technique described in this work enables the measurement of the refractive index fluctuations in a turbulent premixed butane-air flame, by means of an interferometric method in which a laser beam is sent into the flame. More precisely, this technique uses a two-holes interference pattern which undergoes disturbances caused by the flame, and the experimental value of the structure coefficient of refractive index fluctuations is obtained from the measurement of the variance of the random displacement of the central bright fringe.

This paper represents a continuation of our previous works [9–11]. In [9], our research team found the theoretical predictions of the correlations of deflection angles of a laser beam propagating in a hot turbulent jet of air. To confirm these results, experimental investigations in which the laser beam produces a luminous trace on a position photocell placed outside the jet were carried out [9].

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From the examination of this luminous trace, the measurements of the probabilities of the positions of the laser beam impact on the photocell were performed and the results thus obtained were used to measure the structure coefficient of refractive index fluctuations. Some results obtained in [9] are exploited in this work. The flame studied in this paper has already focused our interest in a previous work [10], under the same experimental conditions. In [10], the theoretical predictions and the experimental validation of the angle-of-arrival probability density of a laser beam in the flame were investigated. The interferometer set-up described in this paper was previously used [11] to measure directional fluctuations of a laser beam propagating in a heated wind tunnel jet. The relationship between the laser beam perturbations and the random disturbances of the interferometer pattern has been already demonstrated [11].

In the above works [9–11] which are related to this paper, we have assumed that the laser beam remains sufficiently narrow along its whole path in the turbulent media considered, such that the diffraction effects are negligible compared to the refraction effects. This occurs when the following conditions are met [12–17]:

- The incident wavelength λ of the unperturbed laser beam radiation is very small compared to the inner scale L_i of the turbulent inhomogeneities in the hot jet or the flame considered ($L_i = 1$ mm [6,10,13]).
- The whole path distance Z_m traversed by the laser beam is very great compared to the outer scale L_0 of the turbulent inhomogeneities ($L_0 = 10$ mm [6] for the hot jet and $L_0 = 6$ mm [10] for the flame studied).
- The size of the first Fresnel zone $\sqrt{\lambda Z_m}$ is smaller than the inner scale L_i.

These conditions allow the applicability of the geometrical optics approximation. Under this assumption, the random propagation of the laser beam in the turbulent medium may be approximated as a geometric walk process in which the laser beam only undergoes change in direction such that the light beam can be regarded as a laser ray. In subsequent works, the results presented in this paper would be extended to obtain information about thermal turbulence in combustion chambers.

For a better understanding of this work, the paper contains seven sections: Section 2 is devoted to the theoretical part of the work: the definition of the structure coefficient of refractive index fluctuations is given and its importance is explained. The experimental set-up is presented in Section 3. The measurements performed in the absence of the flame are described in Section 4. The experimental investigations in the presence of the flame are carried out in Section 5. In this section, the experimental procedure which enables the measurement of the structure coefficient of refractive index fluctuations is explained and the results obtained are presented. The verification procedure of these results is done in Section 6. The conclusion is given in Section 7.

2. Theory: definition and importance of the structure coefficient of refractive index fluctuations

When investigating the properties of the turbulence in the flame or in any heated turbulent medium, one usually studies the structure function $\sigma_\mu(\mathbf{r})$ of refractive index which uses the refractive index fluctuation μ evaluated for two positions vectors $\mathbf{x}$ and $\mathbf{x}+\mathbf{r}$, and which is defined as: [18,19]:

$$\sigma_\mu(\mathbf{r}) = \overline{(\mu(\mathbf{x}+\mathbf{r}) - \mu(\mathbf{x}))^2} \tag{1}$$

Using the same research strategy developed by Kolmogorov [20] about the equilibrium zone of turbulence, that is, the zone of fine structures of turbulence, Tatarskii [18] demonstrates that $\sigma_\mu(\mathbf{r})$ depends on the distance $r = |\mathbf{r}|$ and the rate $\overline{\varepsilon}$ of viscous dissipation in the turbulent medium. The quantity $\overline{\varepsilon}$ is defined as:

$$\overline{\varepsilon} = \frac{1}{2}\nu \sum_{i=1}^{3}\sum_{j=1}^{3} \overline{\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2} \tag{2}$$

where x_i or x_j is the component of the vector $\mathbf{x}$, ν is the kinematic viscosity of the turbulent medium, and u_i denotes the component of the speed fluctuation parallel to the x_i axis. More precisely, the structure function is proportional to the quantity $\overline{Q}$ which represents the amount of refractive index inhomogeneities disappeared per unit time because of the molecular diffusion in the heated turbulent medium. $\overline{Q}$ is defined as [18]:

$$\overline{Q} = k\overline{(\mathbf{grad}\,\mu)^2} \tag{3}$$

where k is the refractive index diffusivity of the medium. Taking into account the dimensions of the quantities $\overline{\varepsilon}$, $\overline{Q}$, and r, the following relation is obtained [18]:

$$\sigma_\mu(r) = A^2 \overline{\varepsilon}^{-1/3}\overline{Q}\, r^{2/3} \quad \text{with} \quad L_i \le r \le L_0 \tag{4}$$

where A^2 is a dimensionless constant, L_0 and L_i being the outer and inner scales of turbulence respectively. The positive parameter $A^2\overline{\varepsilon}^{-1/3}\overline{Q}$ which ensures the proportionality relation between σ_μ and $r^{2/3}$, is usually denoted C_μ^2 and is called the structure coefficient of refractive index fluctuations. So, the detailed expression of C_μ^2 is:

$$C_\mu^2 = B^2 k \nu^{-1/3}\left(\sum_{i=1}^{3}\sum_{j=1}^{3}\overline{\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2}\right)^{-1/3}\overline{\left(\left(\frac{\partial \mu}{\partial x_1}\right)^2 + \left(\frac{\partial \mu}{\partial x_2}\right)^2 + \left(\frac{\partial \mu}{\partial x_3}\right)^2\right)} \tag{5}$$

where B^2 is a dimensionless constant connected to A^2 by the relation: $B^2 = 2^{1/3}A^2$. The thermal turbulence in any heated turbulent medium is all the stronger as the structure coefficient C_μ^2 is high.

The second use of the structure coefficient of refractive index fluctuations is its role for the calculation of the turbulence spectrum of the refractive index in the heated medium. About this, it is useful to indicate that the Karman model of turbulence spectrum for the refractive index fluctuations, which is well known to be a realistic and complete model, is written as follows [21,22]:

$$\phi_\mu(K) = \frac{\Gamma(8/3)\sin(\pi/3)}{4\pi^2} C_\mu^2 (K^2 + K_0^2)^{-11/6} \exp\left(-\frac{K^2}{K_m^2}\right) \tag{6}$$

where $\Gamma(8/3)\sin(\pi/3)/4\pi^2 \approx 0.033$, K_0 and K_m are the lower and upper limits of the inertial zone of turbulence defined as: $K_0 = 1/L_0$ and $K_m = 5.92/L_i$, L_0 and L_i being the outer and inner scales of turbulence respectively.

3. Experimental set-up

The experimental setup, which was already used in our previous research team work [11] is shown schematically in Fig. 1. A turbulent premixed flame issued from a rectangular aperture (length = 100 mm, width = 22 mm) of a burner containing a butane-air mixing is traversed perpendicularly to the flow direction of the flame, by a 5 mW He–Ne laser beam. The initial diameter of the laser beam is $a = 0.8$ mm and its incident wavelength is $\lambda = 6328$ Å. The turbulent flame is the same as that already used in our previous work [10].

After having traversed the flame, the perturbed laser beam enters into an interferometric system before reaching a plane where the aperture of a photomultiplier (PM) is placed. This optical system contains two thin lenses L_1 and L_2 (focal lengths $F_1 = F_2 = 100$ mm), two lenses l_1 and l_2 (focal lengths $f_1 = 17$ mm,