Concentration fields in a confined two-gas mixture and engine in-cylinder flow: laser tomography measurement by Mie scattering

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Abstract  Gaseous mixture concentration characterisation by Mie scatter laser tomography has been widely used, except when experimental conditions turn out to be difficult especially in confined flow. This paper describes a complete formulation of the image processing required for a confined flow including effects from wall reflection, quality of the seeding, thermodynamic flow characteristics and instantaneous laser profile disparity. Two applications are described; the first one on a free and confined jet (turbulent, isothermal, isobaric flow) which shows the potential of the technique and the processing needed to reconstitute the mean concentration field, thus demonstrating the reliability of the processing. Second, an in-cylinder engine concentration measurement is put forward. Normal running and a stratified concept are given as examples. The results show the excellent potential of the technique to help engine developers. Thus, this paper presents the problems connected with measurement of concentration fields by laser tomography and Mie scattering from a theoretical and experimental approach.

List of symbols
- $C_i$ Concentration of the species “$i$” (mol × m$^{-3}$)
- $d$ Diameter of a particle (m)
- $D$ Aperture diameter of the lens (m)
- $d_0$ Lens-particle distance (m)
- $f$ Focal length (m)
- $G$ Magnification, image lateral dimension/object lateral dimension (–)
- $I^d_u$ Spectral phase function, function of wavelength, particle diameter $d$, refractive index and scattering angle
- $I^{D_{eq}}_u$ Spectral phase function for an equivalent diameter
- $n$ Mole number (mol)
- $N_p$ Particle density (m$^{-3}$)
- $N_{d}^p$ Particle density for ‘$d$’ diameter (m$^{-3}$).
- $z_i$ Seeding density of the species $<<1>>$ (mol$^{-1}$)
- $\Delta V$ Finite parallelepiped volume (m$^{-3}$)
- $\Delta x$ x dimension of a pixel sensor (m)
- $\phi^{AV}_{inc}$ Incident radiant flux arriving into a finite volume (W)
- $\phi_{refl}$ Wall and rescattered reflection flux (W)
- $\phi_{scn}$ Total radiant flux emitted by the particles (W)
- $\phi_{2cn}$ Radiant flux emitted by the particles in the case of an uniform particles density (W)
- $\tau$ Transmission factor of the lens (–)

1 Introduction

In many fields of application in physics, the knowledge of concentration fields in a gaseous mixture is often necessary to understand phenomena: for example, the study of reactive species and their influence on the operation of certain machines. This information can be obtained by numerical simulation and by using experimental techniques (Merzkich 1974). When the latter are intrusive, they give access either to global values which have been averaged in space and time (Amman 1985, Lorusso et al. 1980), or to instantaneous local values (Li et al. 1994, Lorusso et al. 1980). When optical techniques are chosen, the studied mixture can be characterised by its properties to generate, transmit or absorb electromagnetic radiation. When the phenomena have to be characterised in a topological way, holographic interferometry and laser tomography present a certain advantage over techniques using integration in a measuring volume such as absorption spectrometry, interferometry, stroscopy, ombroscopy (Witze et al. 1981). Last but not least, techniques using fluorescence (Zhao and Ladommatos 1998, Berckmüller et al. 1996) or Mie scattering (Mie 1908, Becker et al. 1967a, b, Birch et al. 1978) possess the qualities required for measuring concentration fields in a two-gas mixture.

Laser Mie tomography is a technique difficult to use in the case of a confined flow such as in-cylinder engine applications. The first section below investigates the right formulation of image processing in order to take into account the different key-points of the measurement. For instance, the flow is represented by a cloud of particles and the laser profile is spatially and temporally non-uniform. The validation in a free and confined jet is considered. Comparisons with theoretical results are made, showing the capabilities of the processing to reconstitute average concentration fields. The technique has already been validated by numerous papers in that field (Chao et al. 1990, Long et al. 1979, 1981a, Becker et al. 1967b, Rosensweig et al. 1961). A more delicate application of this technique consists of measuring the gaseous mixture concentration inside the engine.
cylinder. A better knowledge of the concentration field (Fansler et al. 1995, Tabata et al. 1995, Spiegel and Speicher. 1992), (air/fuel, air/residual gases or air exhaust recycled gases) is expected when developing a new concept engine (variable aerodynamic, throttle in admission pipe) or new combustion process (auto-ignition for spark ignition engine).

2 Concentration expression

Using the laser tomography technique, the flow characteristics (concentration fields or velocity fields) can be represented by particles when experimental precautions are taken. The assumption is made that the particle follows the convective bulk motion of the material of the seeded stream. The nature of the flow may induce particle trajectories different from those of the molecules. Thus, we consider an average approach, \( \langle C(t) \rangle = \overline{C} + C^*(t) \), and we can write for a mixture of two gases a and b homogeneously seeded with two respective seeding densities \( x_a \) and \( x_b \):

\[
\overline{N}_p(X, Y, t) = x_a \cdot \overline{C}_a(X, Y, t) + x_b \cdot \overline{C}_b(X, Y, t)
\]

with \( X, Y, Z \) the co-ordinates in the measuring plane.

Measurement of the absolute seeding density \( x_i \) may prove to be difficult. In order to break free from this calibration, all the equations will be written in a relative spatial difference, \( \frac{\Delta \overline{N}_p}{\overline{N}_p(l)} \) for the particle density existing between two volumes \( \Delta V_j \) and \( \Delta V_k \), respectively centred on points \( l \) and \( k \) belonging to the measuring volume. The hypothesis of a perfect gases is adopted to establish a relationship between the gas species concentration variation and the particles density variation depending on the thermodynamic conditions. When developing Eq. 1 \( \frac{\Delta \overline{N}_p}{\overline{N}_p(l)} = \frac{x_a (\overline{C}_a - n_a) + x_b (\overline{C}_b - n_b)}{x_a \overline{C}_a + x_b \overline{C}_b} \) and using the perfect law, \( C = \frac{\rho}{\rho} = \frac{n x}{\overline{m}_x} \) which is decomposed as \( C = \frac{1}{\overline{m}_x} \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime} \)

with \( \frac{\overline{m}_x}{\overline{m}_x} = 0 \) and \( \overline{C} = \overline{C}_a + \overline{C}_b = \frac{1}{\overline{m}_x} \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime} \)

\( C = C_a + C_b = \frac{1}{\overline{m}_x} \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime}, \overline{C} = 0 \)

we obtain:

\[
\frac{\Delta \overline{N}_p}{\overline{N}_p(l)} + 1 = \left[ \frac{\Delta \overline{C}_a}{\overline{C}_a(l)} + 1 \right] \cdot \left[ \frac{\Delta \overline{p}}{\overline{p}(l) + 1} \right]
\]

Where \( \overline{C}_a = C_a + \frac{C_a \cdot \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime}}{\overline{m}_x} + \frac{\Delta \overline{m}_x}{\overline{m}_x} \left[ \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime} \right]^{-1} \left( \frac{\overline{p}}{\overline{p}(T)} \right) \frac{1}{R} \)

\[
= C_a + \left[ \Delta \overline{m}_x \left( \frac{\overline{m}_x}{\overline{m}_x} \right)^{\prime} \right]^{-1} \left( \frac{\overline{p}}{\overline{p}(T)} \right) \frac{1}{R}
\]

The local thermodynamic conditions are represented by \( \rho \), by its fluctuation, and the concentration \( C_a \). The next step is to express a relationship between the particles density and the radiant flux obtained by the scattering process.

3 Measurements by Mie scattering applied to a cloud of particles

In the case of a cloud of monosized particles exposed to an incident radiant flux \( \phi^\text{inc} \) (laser or light source) by a sheet of light (laser tomography), the flux \( \phi^\text{AV} \), which is scattered by particle density \( N^d_p \), located in a small finite volume \( \Delta V \), and collected by a lens of magnification \( G = \frac{A}{A^\prime} \) (Fig. 1), is expressed by

\[
\phi^\text{AV}(x, y, t) = k \cdot \frac{d^2}{dx^2} \cdot \frac{\Delta x}{d^2} \cdot \tau(x, y) \cdot I^d(X, Y)
\]

\[
\cdot N^d_p(X, Y, t) \cdot \phi^\text{inc}(X, Y, t)
\]

(\( k \) is a numerical constant)

Such an expression includes a number of hypothesis about the seeding (spherical particles, low seeding concentration) and is applied in this case to an effective laser wave band \( \Delta \lambda \). The experimental setting defines the relation existing between \( X, Y, Z \) and \( x, y \). But generally, the radiant flux generated by the volume of measurement does not arise only from the particle

![Fig. 1. Flux scattered by a cloud of particles](image-url)