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Influence of refraction and divergence of light on tomography of axisymmetric laminar diffusion flames

Loreto Pizzuti *, Fernando de Souza Costa

Combustion and Propulsion Associated Laboratory, National Institute for Space Research, Rodovia Presidente Dutra, km 40, Cachoeira Paulista, São Paulo, Brazil

HIGHLIGHTS

- ▶ Influence of divergence and refraction on flame tomography.
- ▶ The divergence influence decreases with flame-camera distance.
- ▶ The divergence influence decreases with confining tube thickness.

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ABSTRACT

Computerized tomography is a non-intrusive diagnostic technique that can be used to analyze flame structure. This work describes a new algebraic algorithm for tomographic reconstruction of confined laminar axisymmetric flames, considering effects of refraction and divergence of light. A flame cross section is divided in a number of concentric rings of constant refraction indexes with the light rays being refracted at ring interfaces. The algorithm is initially tested with a theoretical flame model placed at different camera distances, with several digital camera resolutions and with different thickness of the confining flame quartz tube. Then, the algorithm is applied to the reconstruction of CH^* and C_2^* emissions in co-flow diffusion flames, considering refraction throughout the flame and across the burner quartz tube. The influence of refraction and divergence of light on flame tomography reconstruction appears to be significant depending on the parameters values chosen for the theoretical and experimental setup.

1. Introduction

Fossil fuel burning produces most part of the energy consumed in the world today and, according to the US Energy Information Administration (2011) [1], it will remain the most significant source of energy in the next decades. Conventional combustion technologies, employed in internal combustion engines, gas turbines, thermoelectric power plants, heaters and other devices, are responsible for environmental problems such as greenhouse effect, ozone layer destruction, release of toxic gases, particulate emissions, among other issues.

As a consequence, there is a strong motivation for improvement of diagnostic tools in order to analyze and control combustion processes, aiming to reduce fuel consumption and pollutants emission. Among these tools, computerized tomography (CT), that is a non-intrusive diagnostic technique that allows 3D reconstruction of flame structure, enabling determination of temperature fields, distribution of reactive species and soot, local conditions of mixture and heat release, flame propagation velocity and other properties [2,3].

Tomography is the imaging of an object from its projections obtained by transmission, emission or reflection of light, radiation, sound or particles. Tomography made by measuring the chemiluminescence of species present in the flame is called emission tomography (ET).

Several tomography reconstruction techniques have been previously developed, e.g., using Fourier transforms and algebraic algorithms [4]. Application of numeric techniques to invert the Abel equation, with numerical derivation and integration, can introduce significant reconstruction errors [5,6]. Algebraic reconstruction techniques (ARTs) may allow object reconstruction with a smaller number of projections than other methods or with non-uniform projections. In the limit case of axisymmetric objects, just one projection is sufficient for the object reconstruction, but a generalized inverse reconstruction is very sensitive to noise, especially near the axis of revolution [7,8].

Analyzing the effect of light divergence on the ET reconstruction, an inverse relation between the object–detector distance

* Corresponding author. Address: Technological Institute of Aeronautics, Praça Marechal Eduardo Gomes, no 50, Vila das Acácias, 12.228-900, São José dos Campos, Brazil. Tel.: +55 12 81316664; fax: +55 12 31011992.

E-mail addresses: loretopizzuti@gmail.com (L. Pizzuti), fernando@lcp.inpe.br (F. de Souza Costa).

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Nomenclature

a	inner radius of fuel tube (mm)
b	inner radius of oxidant tube (mm)
d_{FC}	flame-camera distance (mm)
h_q	quartz tube thickness (mm)
n	index of refraction (–)
n_p	number of pixels in a line of the camera's sensor (–)
p_i	projection data along the ith ray (–)
r	radial coordinate (mm)
s	stoichiometric mass fraction (–)
s_{ij}	partial areas (mm^2)
z	vertical distance from fuel tube exit (mm)
DoF	depth of field (mm)
$F\#$	F-number (–)
J_0, J_1	Bessel functions of first kind (–)
L_{theo}	theoretical flame length (mm)
P	projection vector (–)
Pe_n	Peclet number for λ_n (–)
R_G	molar refractivity (cm^3/mol)
S	matrix of partial areas s_{ij} (mm^2)
T	local temperature (K)
T_0	temperature at standard conditions (K)
V_F	fuel velocity at burner exit (mm/s)
X_i	mole fraction of species i (–)
Y_i	mass fraction of species i (–)
$Y_{i,0}$	mass fraction of species i at burner exit (–)
α_{max}	maximum angle of refraction (rad)
β	refractivity (–)
ε_a	arbitrary analytical emission function (–)
ε_j	emitted radiation in the jth ring (–)
ε	emission profile reconstruction vector (–)
ξ	radial non-dimensional coordinate (–)
η	longitudinal non-dimensional coordinate (–)
ρ	local molar density (mol/cm^3)
ρ_0	molar density at standard conditions (mol/cm^3)
λ_n	nth root of J_0 (–)

Subscripts

f	flame
F	fuel
O_2	oxidant

Superscript

*	electronically excited state

and the divergence of light has been reported [4,9]. Ray deflection due to refraction has been analyzed and visualized by shearing interferometry technique [10] and by deflectometric methods [11,12]. Those techniques for ray deflection analysis require lasers for light beams generation and a system of mirrors to produce a collimated beam.

Some of the most relevant recent research in the tomography area has aimed to investigate 2D and 3D flames either by using multi lens CCD cameras or crossed-plane laser tomography.

The 2D chemiluminescence distributions of OH*, where the * denotes an electronically excited state, in reaction zones of a near laminar and a turbulent diffusion flame, registered by ten Kepler-telescopes surrounding the object and imaged onto an intensified CCD camera was performed by Anikin et al. [13]. The reconstructions obtained with exposure times down to 200 μs reproducing fine structures of the flames with a spatial resolution of ~1 mm were applied for the investigation of turbulent diffusion flames [14]. The three-dimensional instantaneous CT reconstruction distribution of chemiluminescence species (CH* and C_2^*) in a premixed propane/air turbulent flame was accomplished by Ishino and Ohiwa by using a custom built, film based, 40 lens camera [15]. Later the same technique was extended to estimate the local burning velocity by acquiring two sequential measurements with time-interval of 1.29 ms [16].

Hossein et al. [17] proposed a tomographic system using two CCD cameras coupled with eight high-specification imaging fiber bundles to produce simultaneously eight image projections around a flame, capable of 3-D visualization and characterization of combustion flames in a practical furnace. Floyd and Kempf [18] used emission-based CT to image a methane–oxygen Matrix burner consisting of 21 laminar diffusion jet flames, accomplishing good agreement between the high resolution 3-D reconstructions from 48 views with the observed flame shape. The resolved wavelength of approximately 220 μm was sufficient to capture the multiple flame fronts, showing the suitability of CT chemiluminescence for wrinkled turbulent flames. Bingham et al. applied crossed-plane laser tomography to premixed turbulent flames obtaining the measure of instantaneous flamelet surface orientation, necessary for the study of reaction sheet wrinkling due to turbulence [19].

Since the light emitted by excited radicals within a flame spreads in all directions and most flames show significant gradients of density and temperature, the present work describes a new tomographic reconstruction algorithm which accounts simultaneously for the influence of divergence and refraction of light on the tomographic reconstruction of laminar axisymmetric diffusion flames. In the reconstruction algorithm the divergence and refractive effects are taken into account by considering divergent optical paths (fan geometry) [4] and by introducing a theoretically calculated refraction index field. The refraction field can be inferred from the temperature field only if the pressure and composition is known at each point within the flame [20]. Thus a cylindrical Burke–Schumann (BS) burner with an external quartz tube was employed to generate laminar axisymmetric diffusion flames of methane (CH_4) and liquefied petroleum gas (LPG) in air at atmospheric pressure. The flame temperature and species distribution fields, applied in the determination of the axisymmetric index of refraction field, are theoretically calculated based on a modified Schvab–Zeldovich solution of the cylindrical BS problem [21]. Tomographic reconstructions are obtained from monochromatic flame images taken with a Charge-Coupled Device (CCD) sensor digital camera coupled with optical filters. A single digital camera was utilized as ET of axisymmetric flames requires only one flame projection.

The findings of the present work may be useful for the flame tomography community by addressing the experimental conditions which lead to minimum divergence and refraction effects on tomography reconstructions of laminar flames. Moreover it shows that refraction and divergence of light have no considerable effect on the tomographic reconstruction of flames of the type investigated in the paper.

2. Tomographic reconstruction algorithm

In the work presented in this paper tomographic reconstruction of local flame scalar properties is based on the deconvolution of a finite number of two-dimensional path integrated measurements of chemiluminescence emitted by flame radicals. Tomographic