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Tomographic absorption spectroscopy for the study of gas dynamics and reactive flows

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ABSTRACT

Optical imaging techniques are ubiquitous for the resolution of non-uniformities in gas flows. Planar imaging techniques such as laser-induced fluorescence are well established and applied extensively in turbulent reactive flows, offering both high temporal and spatial resolutions. However, planar imaging suffers from a critical disadvantage, the requirement for spatially continuous optical access over large solid angles in both the excitation and detection paths and this precludes their application in many practical situations, for example those encountered in engine testing. Tomographic absorption spectroscopy, TAS, on the other hand, shares many of the advantages of planar imaging techniques but reduces the demands for optical access, because high quality data can be obtained with sparsely sampled volumes. The technique has unrivalled potential for imaging in harsh environments, for example for in-cylinder/in-chamber engine measurements. TAS is beginning to mature as a technique for the simultaneous imaging of temperature and species concentration, and is experiencing a surge of interest due to progress in laser technology, spectroscopy, and theoretical developments of nonlinear tomography techniques. The recent advancements in broad bandwidth, frequency-agile laser sources massively enrich the spectral information obtainable in TAS. Furthermore, nonlinear tomography enables the recovery of multiplexed information from a single tomographic inversion. The utilization of multispectral information improves the immunity of TAS to experimental noise and makes possible the simultaneous imaging of temperature, pressure, and multiple species. Nonlinear tomography can also be used to empower the imaging potential of sensitive and robust absorption techniques, such as wavelength modulation spectroscopy, for use in harsh and even optically dense environments. In combination, this greatly extends the applicability of TAS for more general and harsh scenarios in combustion technology. In this article we review basic concepts and mathematical foundations of classical absorption tomography, proceeding to more advanced recent concepts based on nonlinear tomography, and providing an extensive review of experimental demonstrations and practical applications in the context of state-of-the-art combustion research.

1. Introduction

Combustion remains the dominant form of energy production in use today, and is an underpinning factor for modern society [1,2]. This dominance is expected to continue for several decades into the future and thus a full understanding and effective control of combustion processes is of paramount importance to improve energy efficiency and to reduce the formation of pollutant species such as particulates, NO_x, SO_x, and greenhouse gases [3,4]. Key to an understanding of combustion is an ability to measure chemical and physical flow parameters at high temporal and spatial resolution, and to untangle the complex interplay between flow dynamics, chemical kinetics, and heat and mass transfer, which remains a formidable scientific challenge to this day [5]. There are several key parameters such as temperature, species concentration, equivalence ratio, heat release rate, and velocity, the quantification of which is essential to any such effort, and requires their measurement under physically realistic conditions. Numerous non-invasive optical sensing techniques have been developed during the past decades for the diagnosis of reactive flows. For simple laminar flames, such as laboratory McKenna and Bunsen flames, point measurement techniques can be used for the measurement of temperature, such as laser induced grating spectroscopy (LIGS) [6], coherent anti-Stokes Raman scattering (CARS) [7–10], and two-line atomic fluorescence thermometry (TLAF) [11–16]; Laser Doppler velocimetry (LDV) [17,18] for point measurements of local velocity; line-of-sight-averaged techniques such as tunable diode laser absorption spectroscopy (TDLAS) [19,20] for the simultaneous retrieval of temperature, species concentration and pressure; and cavity enhanced techniques (CEAS) [21–26] for

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Nomenclature

p	line-of-sight-integrated absorbance
R [a.u.]	radius of the region of interest
r [a.u.]	distance to the origin
$f(r)$	spatial distribution of absorbance along the radial direction
η	an integration variable
l	laser beam path
x, y	x and y coordinates
Θ [rad]	angle between beam path and x axis
t [a.u.]	distance from origin to the beam path
$\vec{x}$	image pixel values arranged in a vector format
I	total number of beams
J	total number of pixels
$A_{I\times J}$	weight matrix
$\vec{a}_i$	the ith row of A
β	relaxation factor
Θ	a linear operator
$\vec{\Phi}_k$	eigenfunctions
ζ	eigenvalues
L	regularization operator realized in a matrix format
g	regularization factor
R	resolution matrix
I	identity matrix
$\vec{\Psi}$	a vector of complex numbers
R_j	ratio of integrated absorbance at two transitions of the jth pixel
μ	spatial distributions of the flow parameters
Π	a function describing a physical process
Δ	grid spacing
T [K]	temperature
X	absorber concentration
P [atm]	pressure
LIGS	laser-induced grating spectroscopy
TLAF	two-line atomic fluorescence thermometry
TDLAS	tunable diode laser absorption spectroscopy
PLIF	planar laser-induced fluorescence
LIPS	laser-induced phosphorescence spectroscopy
LOS	line-of-sight
ABNT	absorption-based nonlinear tomography
CFWMS	calibration-free wavelength modulation spectroscopy
TPA	three-point Abel
ART	algebraic reconstruction technique
SR	spatial resolution
LSF	line spread function
ESF	edge spread function
ROI	region of interest
MART	multiplicative algebraic reconstruction technique
TRKB	tomographic reconstruction via Karhun-Loeve basis
TSLs	tunable semiconductor lasers
QCLs	quantum cascade lasers
DBR	distributed Bragg reflector
CA	crank angle
α	absorption coefficient
p_c	computed projection
p_m	measured projection
R_T	regularization term for T distribution
R_X	regularization term for X distribution
γ_T	regularization factor for R_T
γ_X	regularization factor for R_X
a [cm^{-1}]	modulation depth
ν [cm^{-1}]	laser frequency
I [a.u.]	laser intensity
i_0 [a.u.]	linear modulation amplitude
i_2 [a.u.]	nonlinear modulation amplitude
σ_m	std of measurement noise
f_m [kHz]	modulation frequency
ψ_1 [rad]	linear phase shift with respect to frequency modulation
ψ_2 [rad]	nonlinear phase shift with respect to frequency modulation
S [cm^{-2}/atm]	line strength
H_k	kth order harmonic coefficients
τ	transmittance
S_{1f} [a.u.] S_{2f} [a.u.]	1st and 2nd orders of harmonic signals
G	scaling factor accounting for electrical and optical gains
$\bar{I}_0$ [a.u.]	average laser intensity at the line-center
F	cost function
T_{SA}	temperature parameter in the simulated annealing algorithm
ξ	annealing rate
e_T, e_X	normalized temperature and concentration errors
T^{true} [K] T^{rec} [K]	ground truth and reconstructed temperature
X_1, X_2	concentration for a two-zone problem
T_1 [K], T_2 [K]	temperature for a two-zone problem
CARS	coherent anti-Stokes Raman scattering
LDV	laser Doppler velocimetry
CEAS	cavity enhanced absorption spectroscopy
PIV	particle imaging velocimetry
FRS	filtered Raman scattering
TAS	tomographic absorption spectroscopy
CAT	classical absorption tomography
SNR	signal-to-noise ratio
FBP	filtered back-projection
MLEM	maximum likelihood expectation maximization
AART	additive algebraic reconstruction technique
SIRT	simultaneous iterative reconstruction technique
MTF	modulation transfer function
PSF	point spread function
DFT	discrete Fourier transform
FDML	Fourier domain mode-locking
TDLs	tunable diode lasers
DFB	distributed feedback
TDC	top dead center
DAS	direct absorption spectroscopy
POD	proper orthogonal decomposition
SA	simulated annealing