A Thermophoretic-Thermocouple Method for Soot Measurement in Combustion

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Istituto di Ricerche sulla Combustione

20th ETH Conference on Combustion Generated Nanoparticles – Zurich – June 13-16, 2016

Introduction and motivations

SOOT FORMATION IN FUEL-RICH FLAME CONDITIONS

Wide range of molecular weights and sizes

Nascent Organic Carbon Nanoparticles
(2-5 nm)

Soot Nanoparticles
(10-100 nm)

Introduction and motivations

SOOT FORMATION IN FUEL-RICH FLAME CONDITIONS

Wide range of molecular weights and sizes

Nascent Organic Carbon Nanoparticles
(2-5 nm)

Soot Nanoparticles
(10-100 nm)

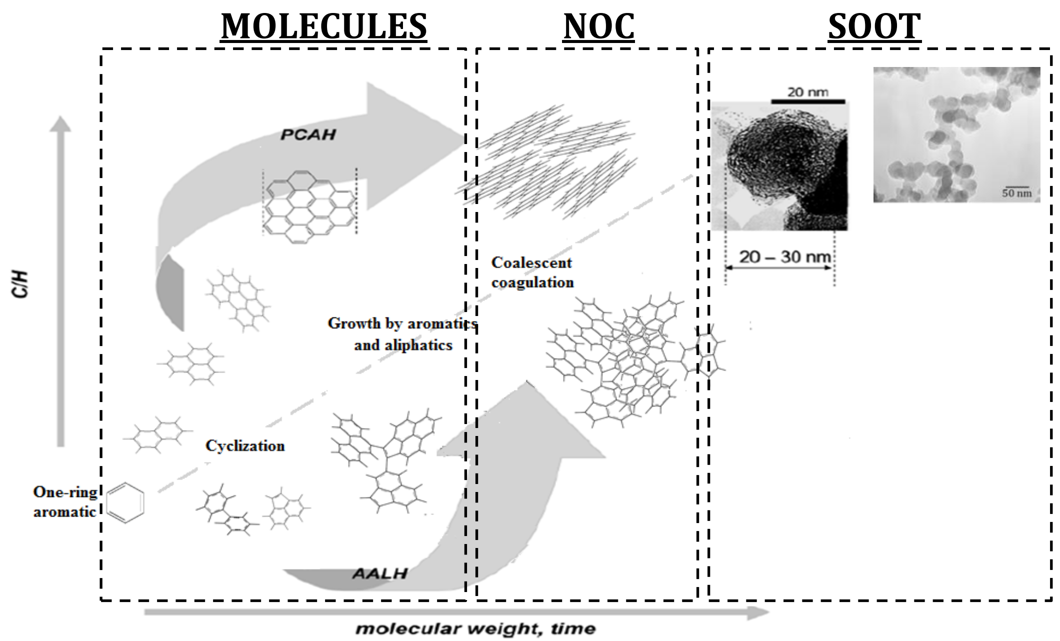
Differentiate by:

- ✓ Size and morphology
- ✓ Chemical composition
- ✓ Optical and spectroscopy properties
- ✓ H/C ratio (organic carbon vs. black carbon)
- ✓ Physical status

H. Bockhorn, *Soot Formation in Combustion.* (1994)   A. D'Anna, *Proc. Combust. Inst.* **32** (2009)   H. Wang, *Proc. Combust. Inst.* ***33*** (2011)

Introduction and motivations

SOOT FORMATION IN FUEL-RICH FLAME CONDITIONS



A. D'Anna, in *Combustion Generated Fine Carbonaceous Particles* (2009)

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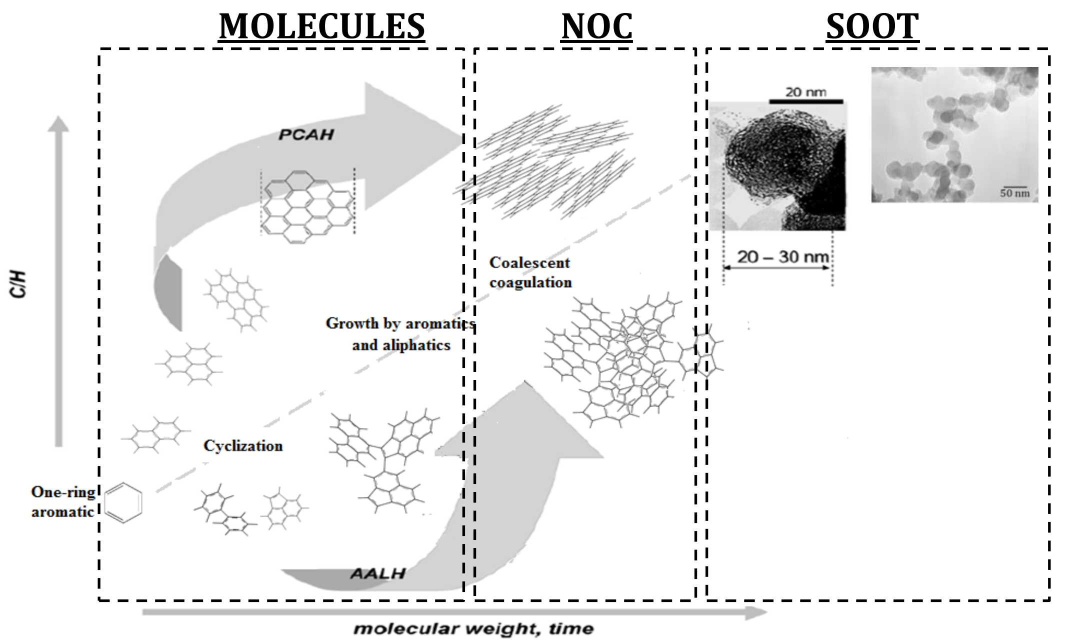

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Diagnostic methods

QUANTITATIVE INFORMATION
(Particle concentration)

QUALITATIVE INFORMATION
(Particle nature and composition)

OBJECTIVE OF THIS WORK

To develop and apply a diagnostic method able to measure *in-situ* in combustion systems:

- **Thermal emissivity of carbon nanoparticles (QUALITY)**
- **Particle volume fraction (QUANTITY)**

TPD-Based Thermophoretic-Thermocouple Method

Thermocouple Particle Densitometry (TPD)

ELSEVIER

Combustion and Flame

Volume 109, Issue 4, June 1997, Pages 701-720

Soot volume fraction and temperature measurements in laminar nonpremixed flames using thermocouples

Charles S. McEnally, Ümit Ö. Köylü, Lisa D. Pfefferle, Daniel E. Rosner

Department of Chemical Engineering and Center for Combustion Studies, Yale University, New Haven, CT 06520-8286 USA

Available online 8 May 1998

Show less

doi:10.1016/S0010-2180(97)00054-0

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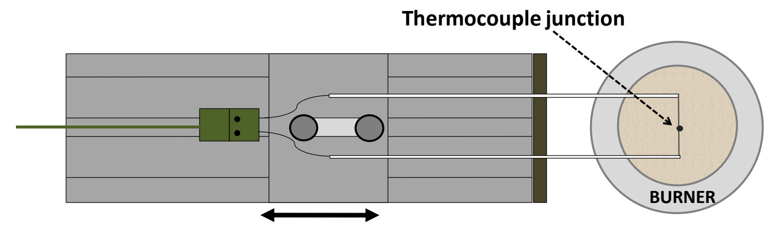
Abstract

Thermocouple particle densitometry (TPD), a new method for measuring absolute soot volume fraction in flames which was suggested by Eisner and Rosner, has been successfully implemented in several laminar nonpremixed flames. This diagnostic relies on measuring the junction temperature history of a thermocouple rapidly inserted into a soot-containing flame region, then optimizing the fit between this history and one calculated from the principles of thermophoretic mass transfer. The TPD method is very simple to implement experimentally, yields spatially resolved volume

RAPID INSERTION PROCEDURE



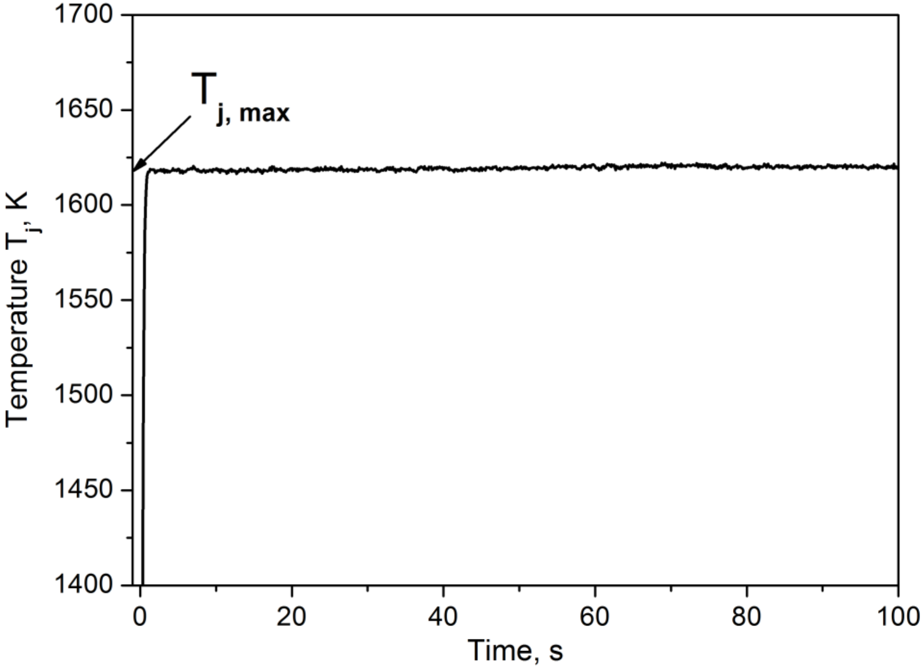
C.S. McEnally et al. *Combust. Flame* **109** (1997)

A.D. Eisner and D.E. Rosner *Combust. Flame* **61** (1985)

TPD-Based Thermophoretic-Thermocouple Method

GAS TEMPERATURE DETERMINATION

Particle-free flame region



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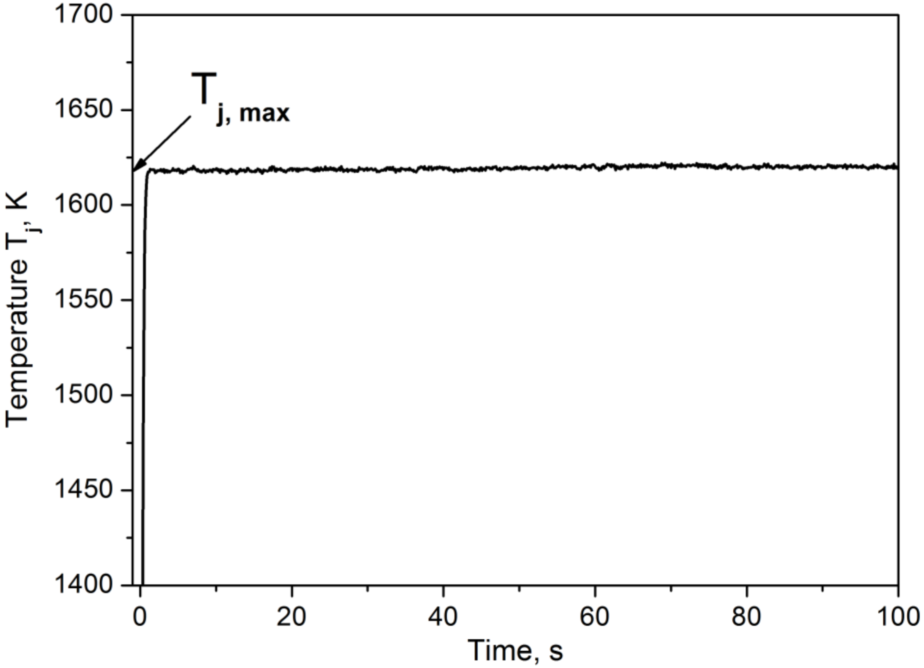
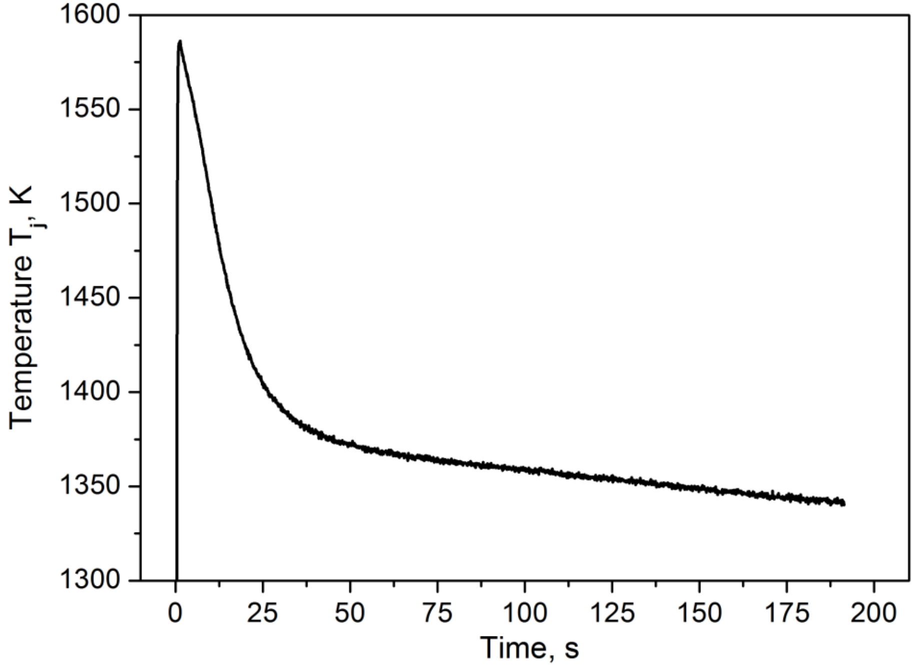


Soot-containing flame region



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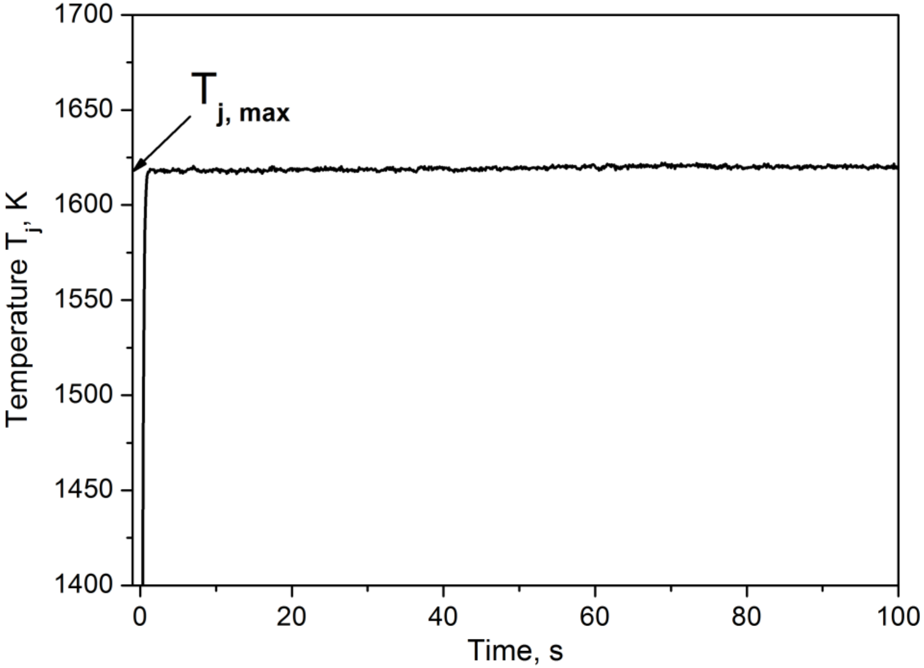

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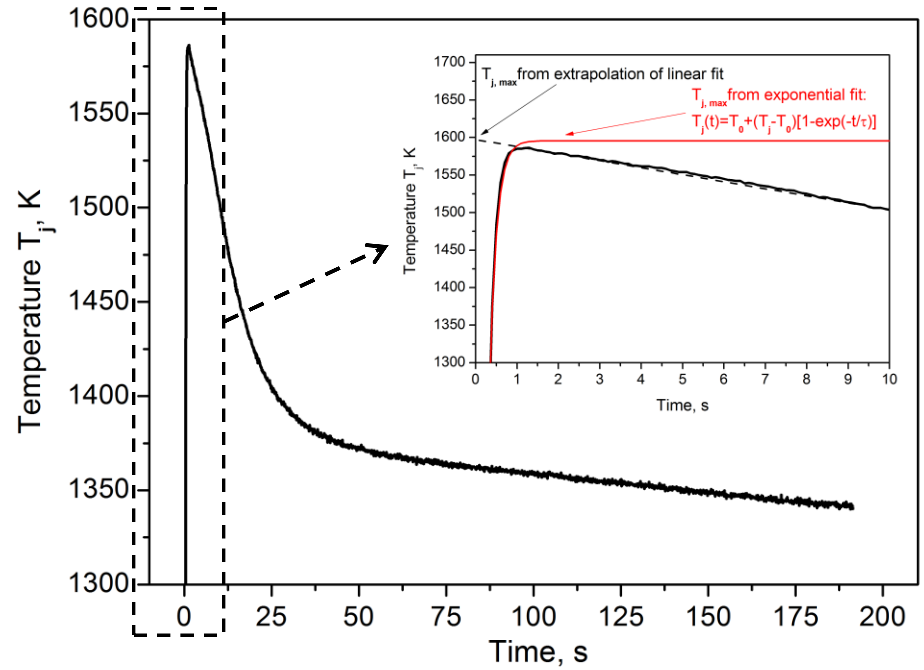

C.S. McEnally et al. *Combust. Flame* **109** (1997)
Z. Xu and H. Zhao *Combust. Flame* **162** (2015)

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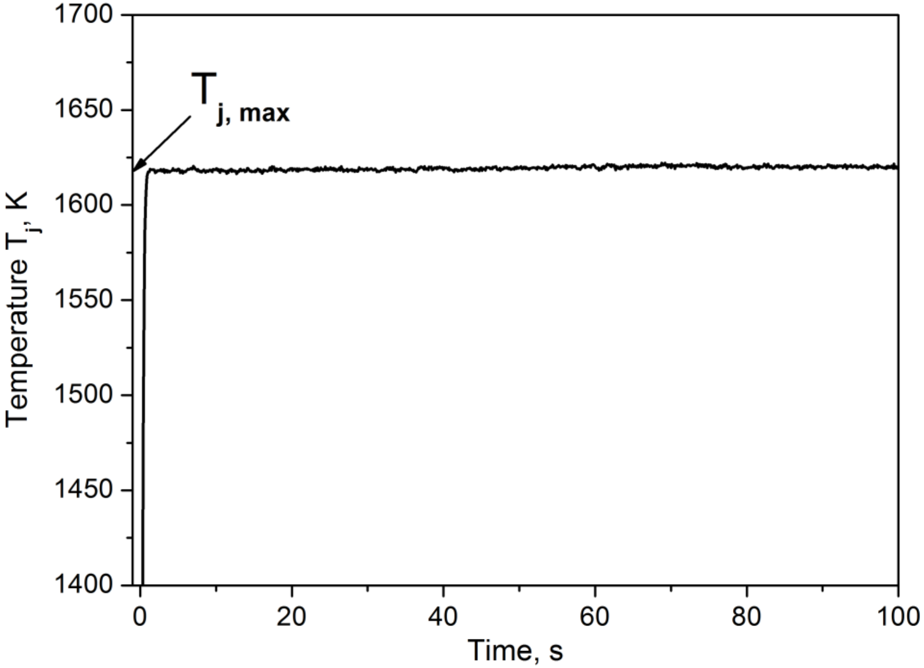

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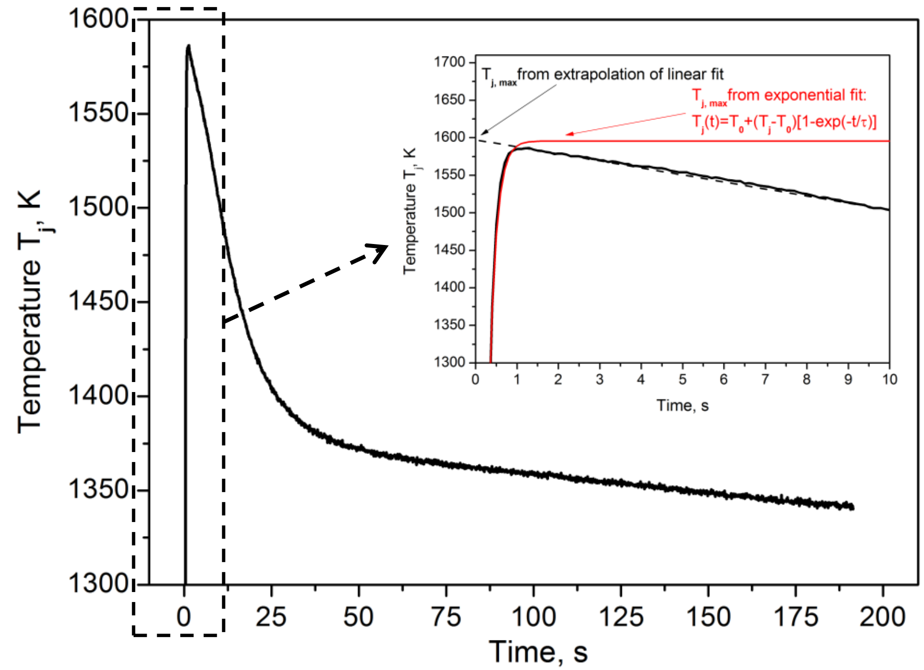

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Energy balance at the thermocouple junction

$$\varepsilon_j \sigma T_{j,max}^4 = \left(\frac{K_{g0} Nu_j}{2d_j}\right)\left(T_g^2 - T_{j,max}^2\right)$$

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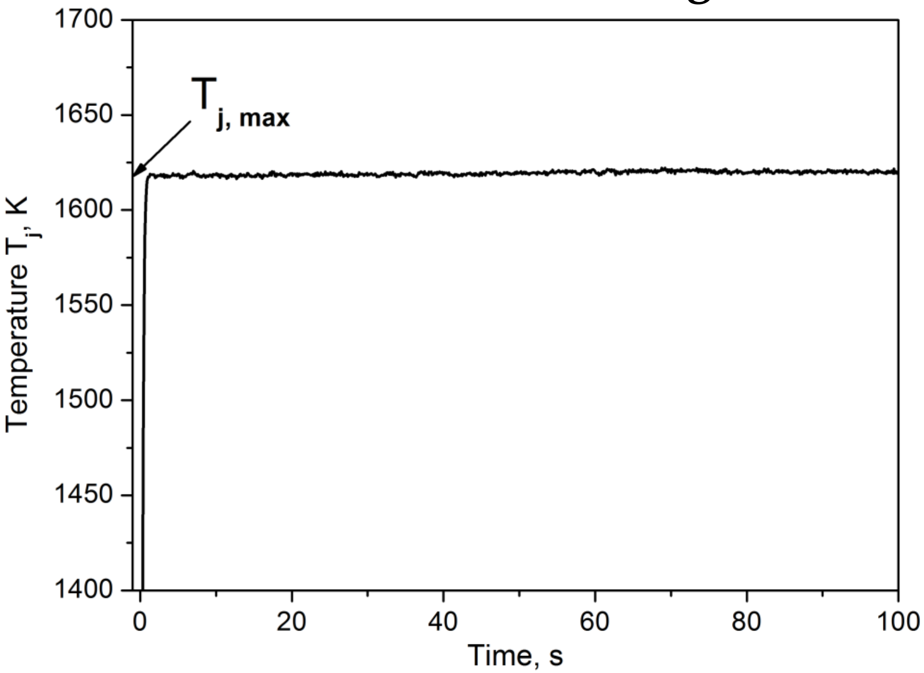

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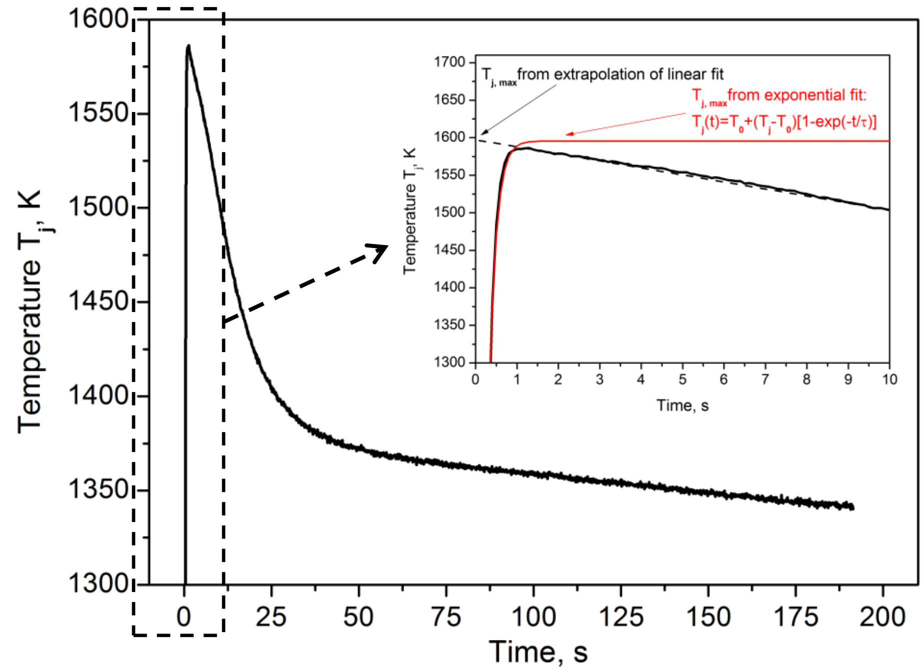

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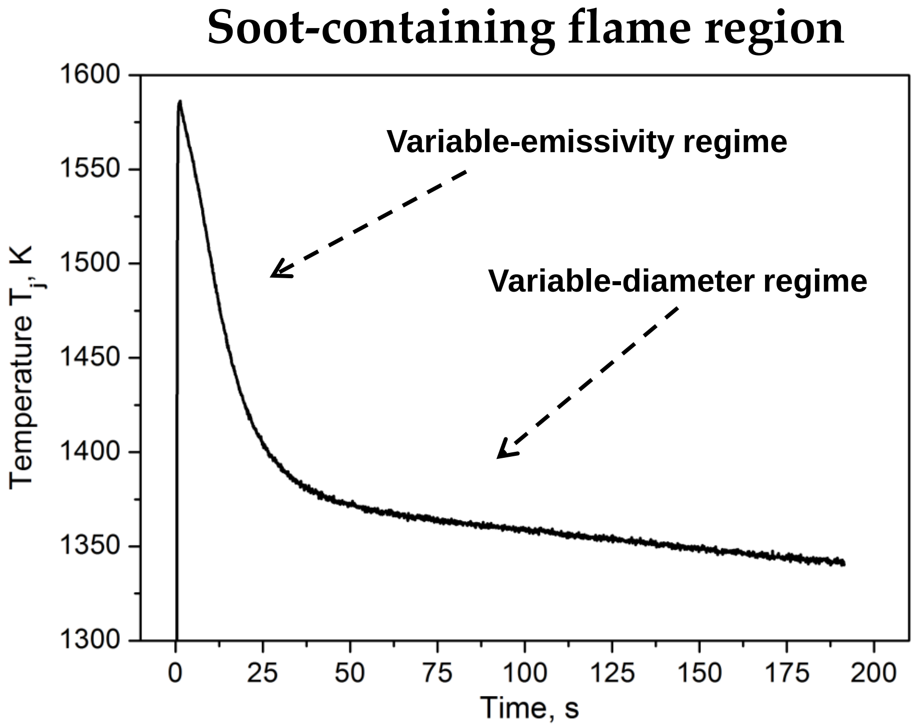
TPD-Based Thermophoretic-Thermocouple Method

PARTICLE EMISSIVITY DETERMINATION



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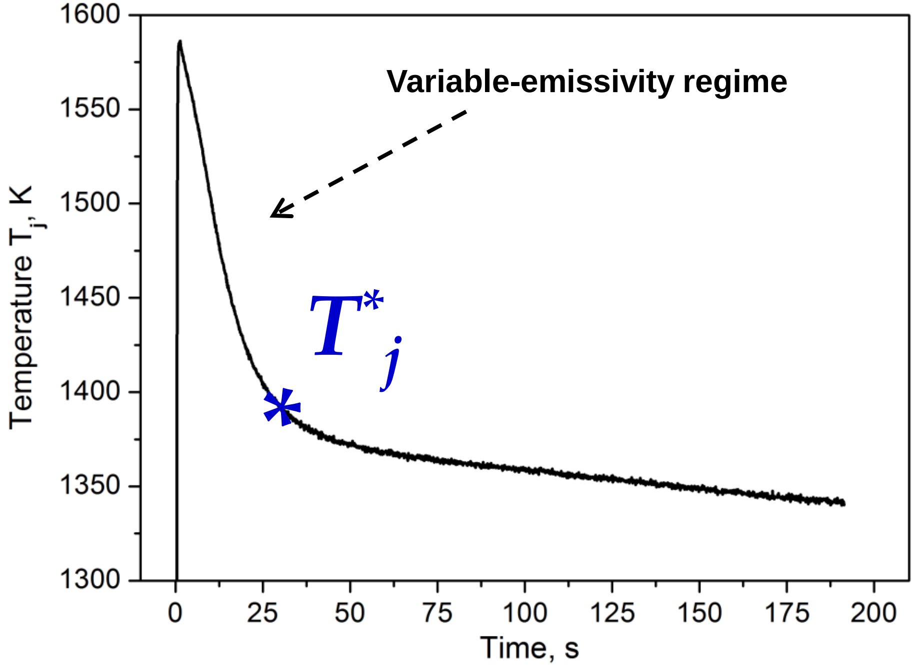

Energy balance

$$\varepsilon_{par}\sigma T_j^{*4} = \left(\frac{K_{g0} Nu_j}{2 d_j}\right)(T_g^2 - T_j^{*2})$$

TPD-Based Thermophoretic-Thermocouple Method

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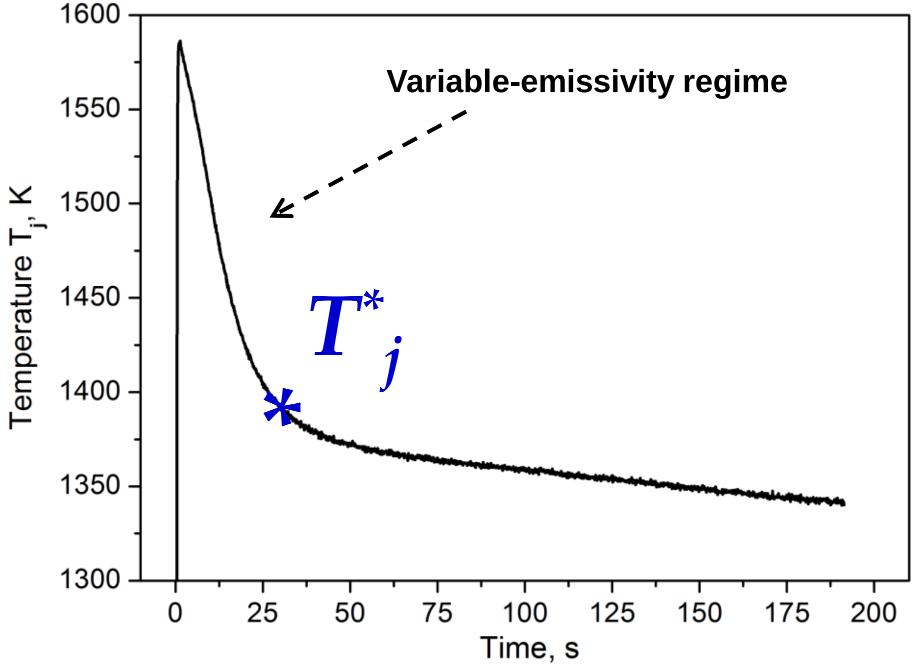

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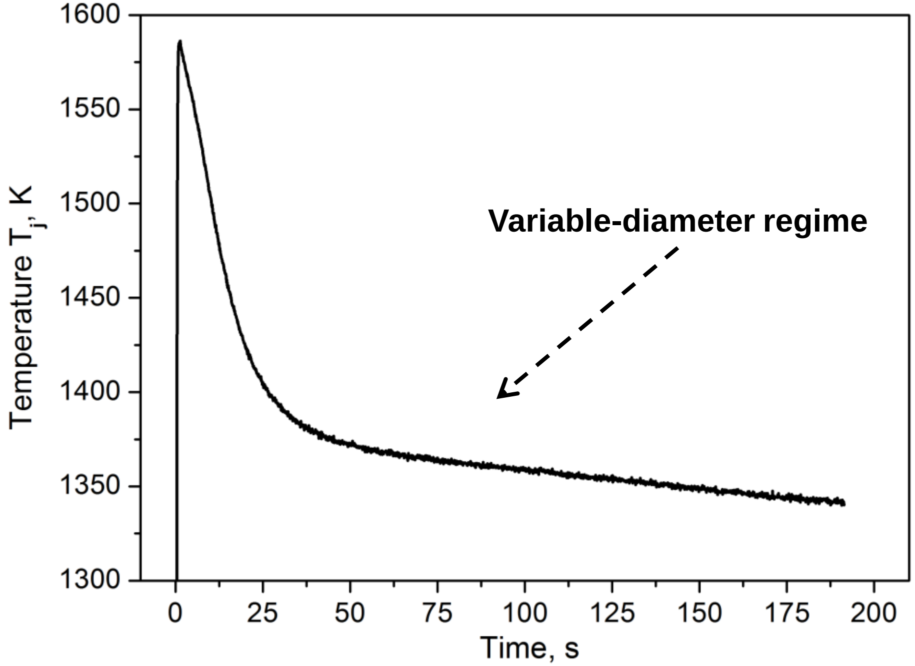
TPD-Based Thermophoretic-Thermocouple Method

PARTICLE f_V DETERMINATION

Soot-containing flame region



Energy balance

+

Mass balance

(Thermophoretic flux)

$$G = \frac{1}{4}\left(\frac{T_g}{T_j}\right)^8 - \frac{1}{6}\left(\frac{T_g}{T_j}\right)^6 = G_0 + \frac{2D_T \varepsilon_{particle}^2 \sigma^2 T_g^4}{(\rho_d/\rho_p)K_{g0}^2 Nu_j} f_v t$$

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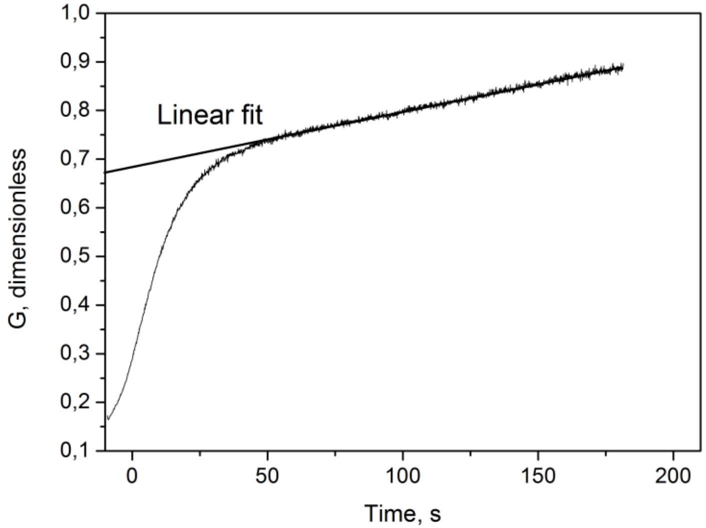

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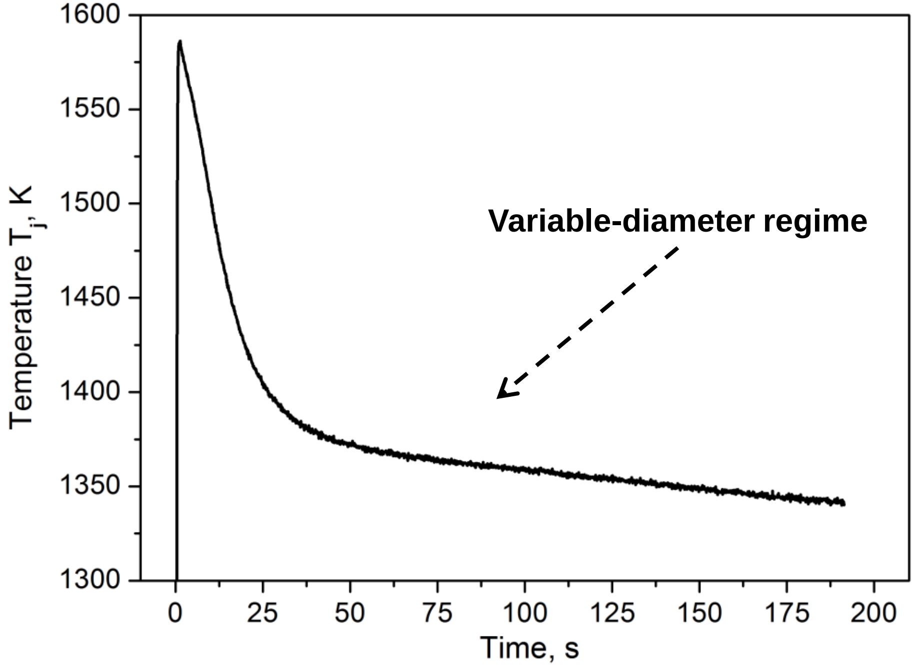

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Laminar Premixed Flame: Method Validation

M. Commodo et al. *Combust. Flame* **162** (2015)

- **Ethylene/Air Laminar Premixed Flame**
- **McKenna Burner**
- **v_{cg}=9.8 cm/s, Φ=2.01**

Type-R thermocouple, bead diameter = 235 μm

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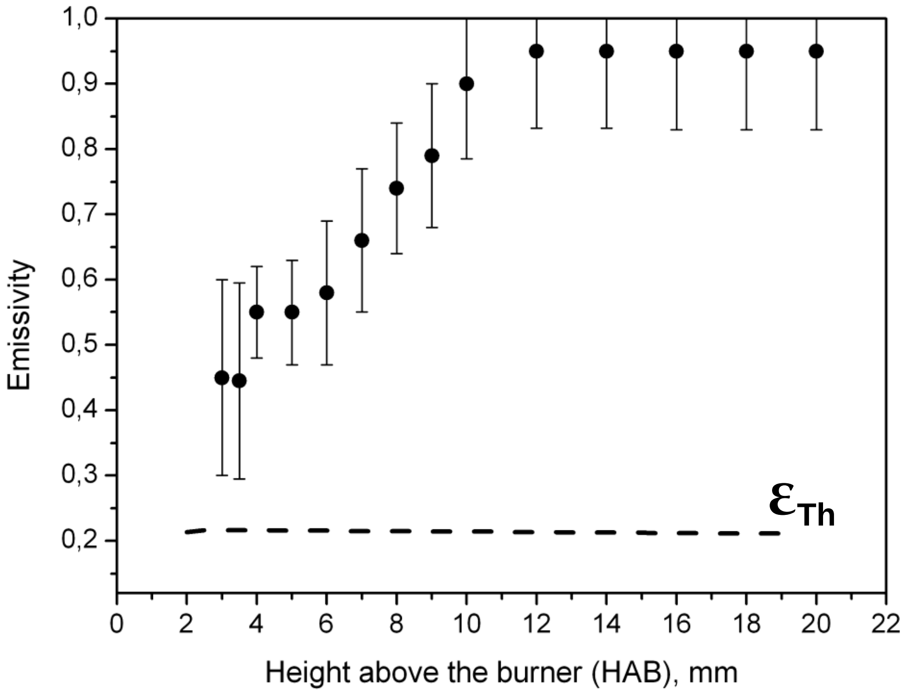

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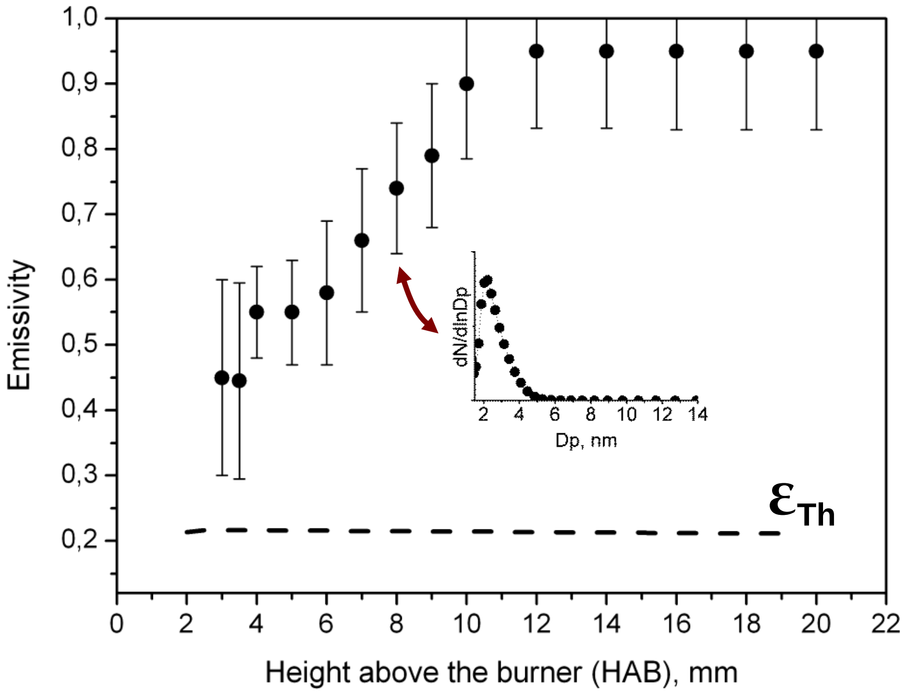

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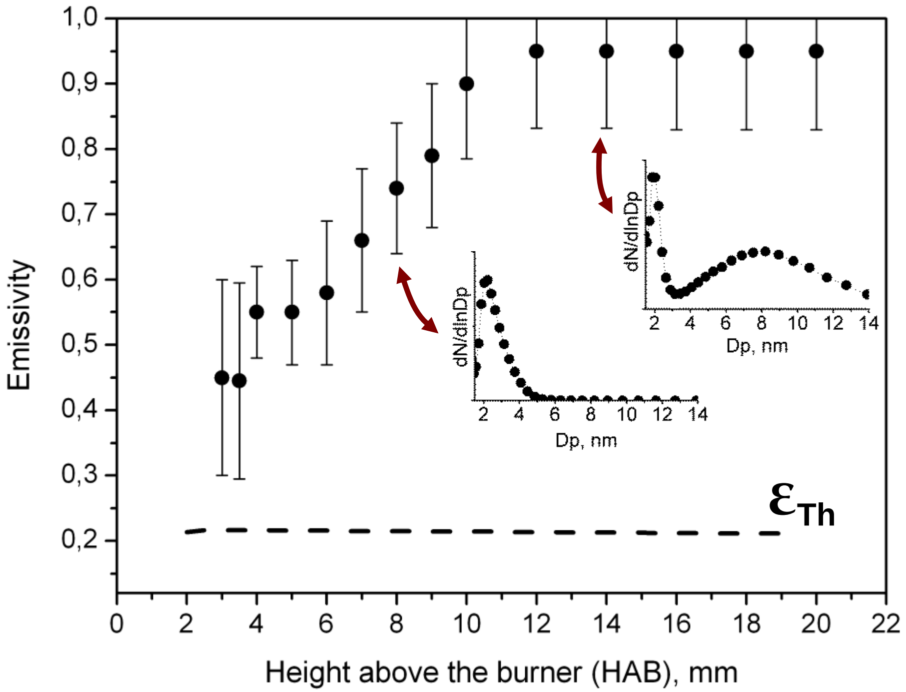

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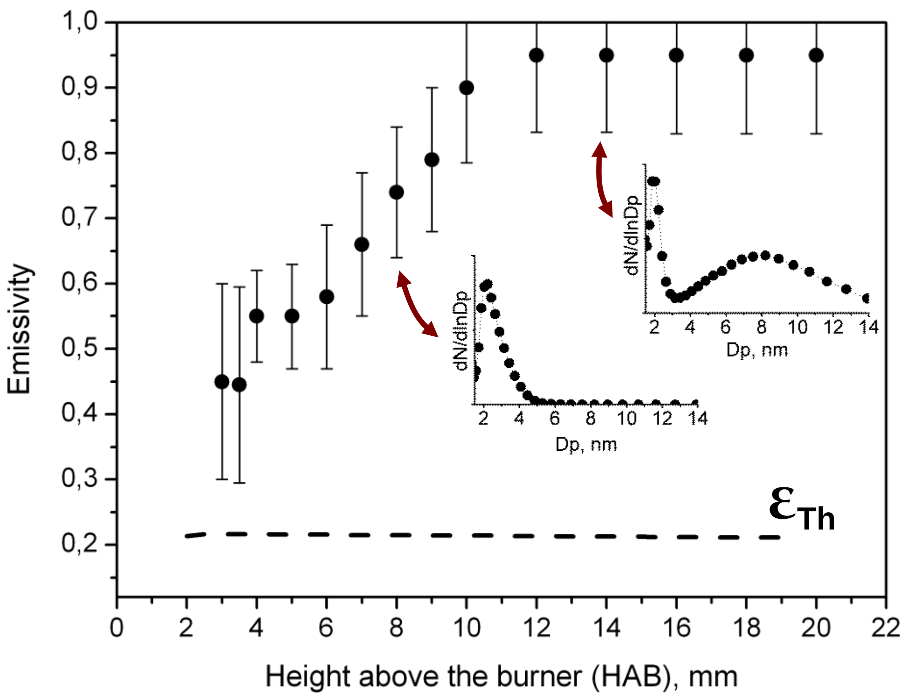

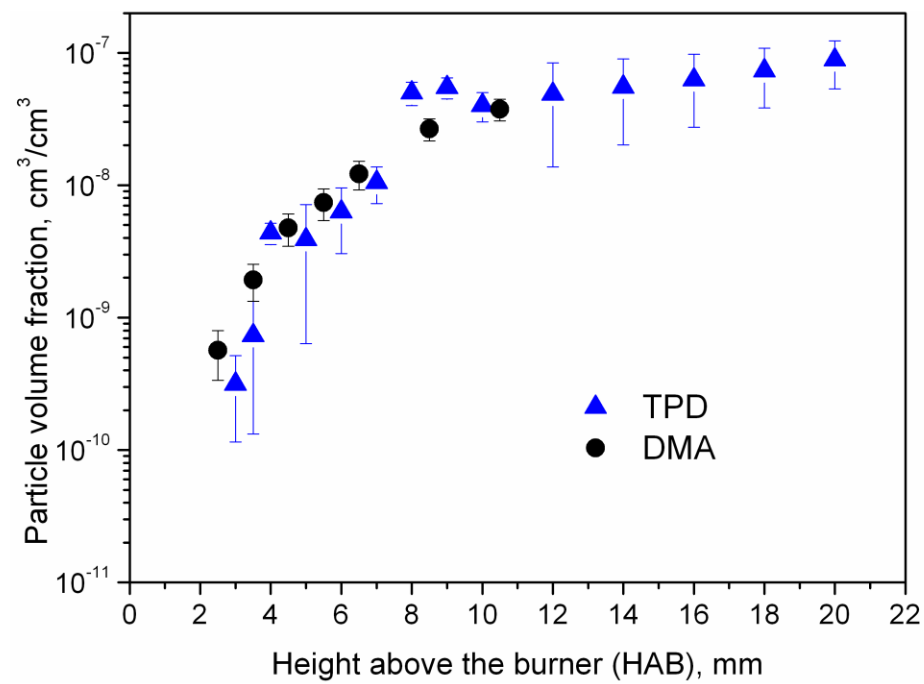

Laminar Diffusion Flame

- Ethylene/Nitrogen Co-Flow Laminar Diffusion Flame
- ISF target flame (ISF-3 Co-flow2, Condition a)

C.S. McEnally and L.D. Pfefferle *Combust. Flame* **121** (2000)

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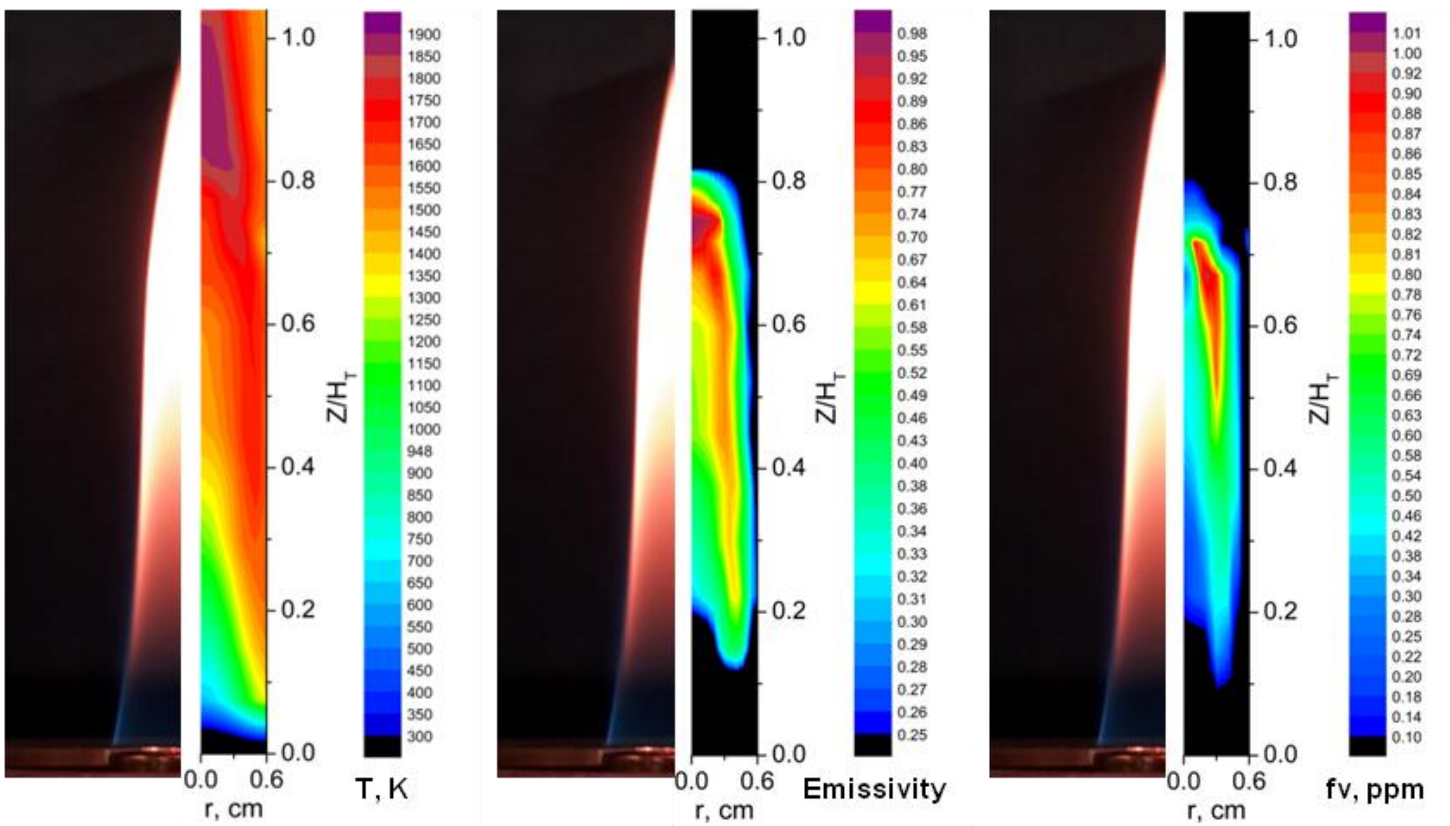

Laminar Diffusion Flame

THE EFFECT OF OXIDATION

MASS BALANCE AT THE THERMOCOUPLE JUNCTION

$$\left(\frac{\rho_d}{2}\right)\frac{d(d_j)}{dt} = \left(\frac{D_T N u_j f_v \rho_p}{2 d_j}\right)\left(1 - \left(\frac{T_j}{T_g}\right)^2\right)$$

(Thermophoretic flux)

Laminar Diffusion Flame

THE EFFECT OF OXIDATION

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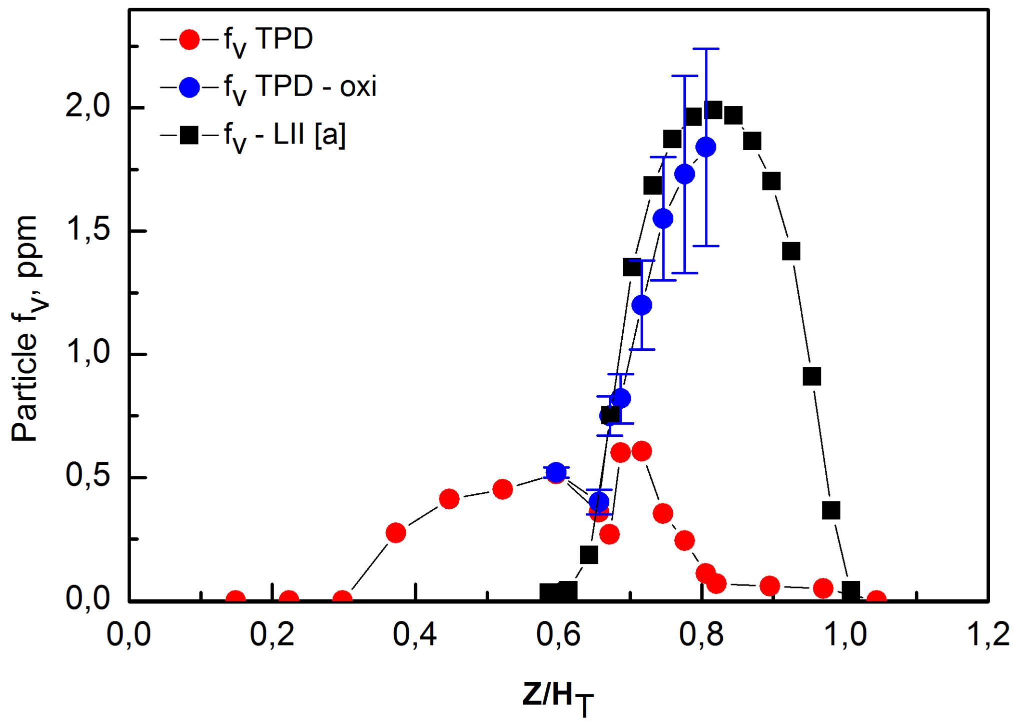
(Thermophoretic flux) *(Soot burnout rate by OH)*

H. Ghiassi et al. *Energy Fuel* **30** (2016)

Laminar Diffusion Flame

THE EFFECT OF OXIDATION



[a] C.S. McEnally and L.D. Pfefferle *Combust. Flame* **121** (2000)

Laminar Diffusion Flame

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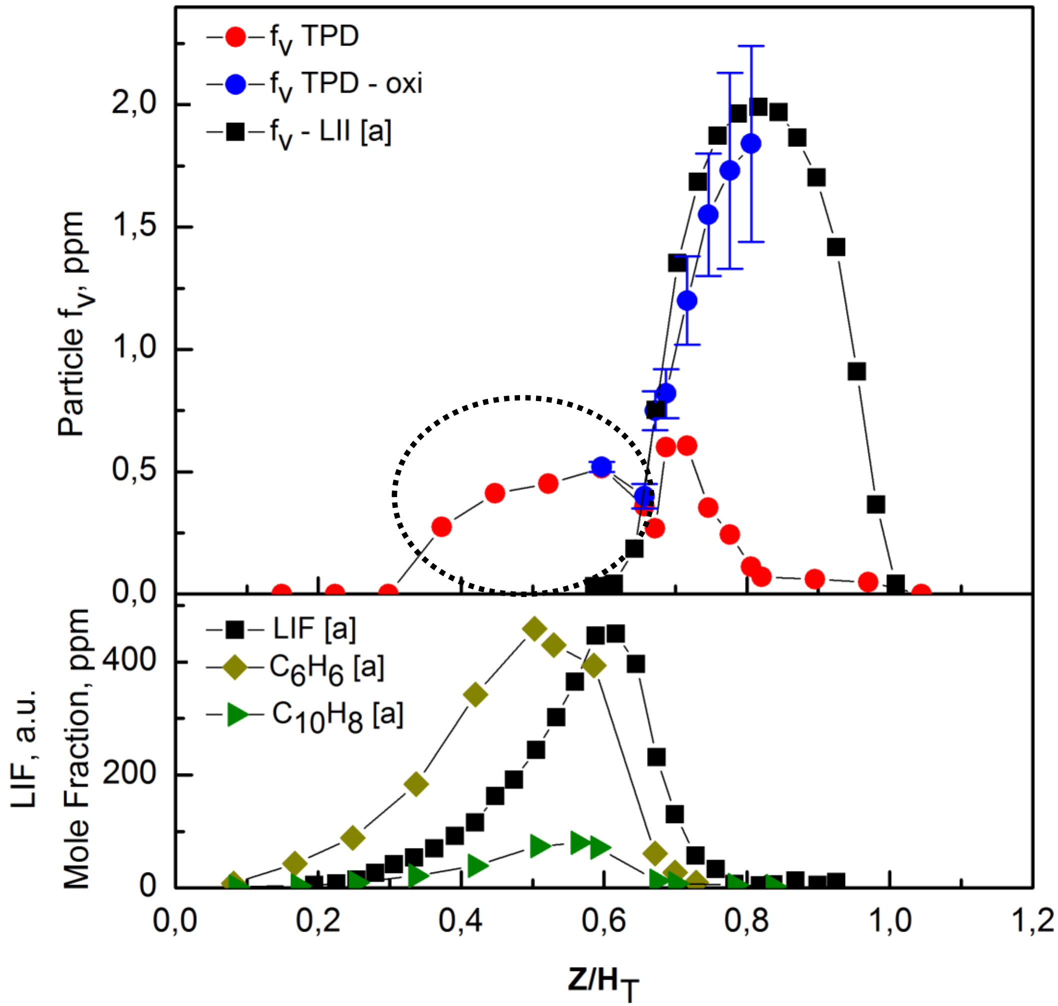

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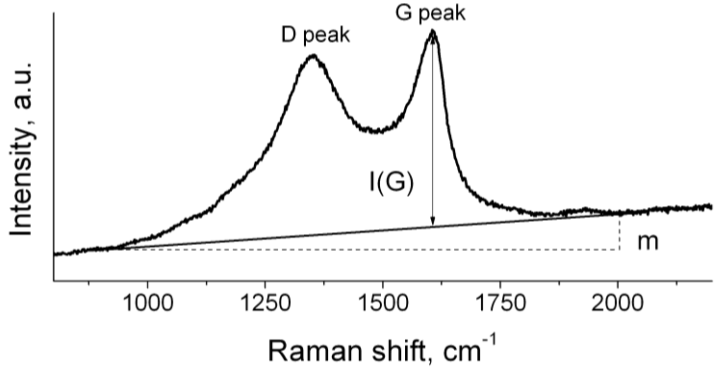
Laminar Diffusion Flame

THE EVOLUTION OF PARTICLE NATURE/COMPOSITION

Raman Spectroscopy



$$\frac{m}{I(G)} = \frac{Fluorescence}{sp^2 Carbon}$$

C. Casiraghi et al. *Diam. Relat. Mater.* **14** (2005)

Laminar Diffusion Flame

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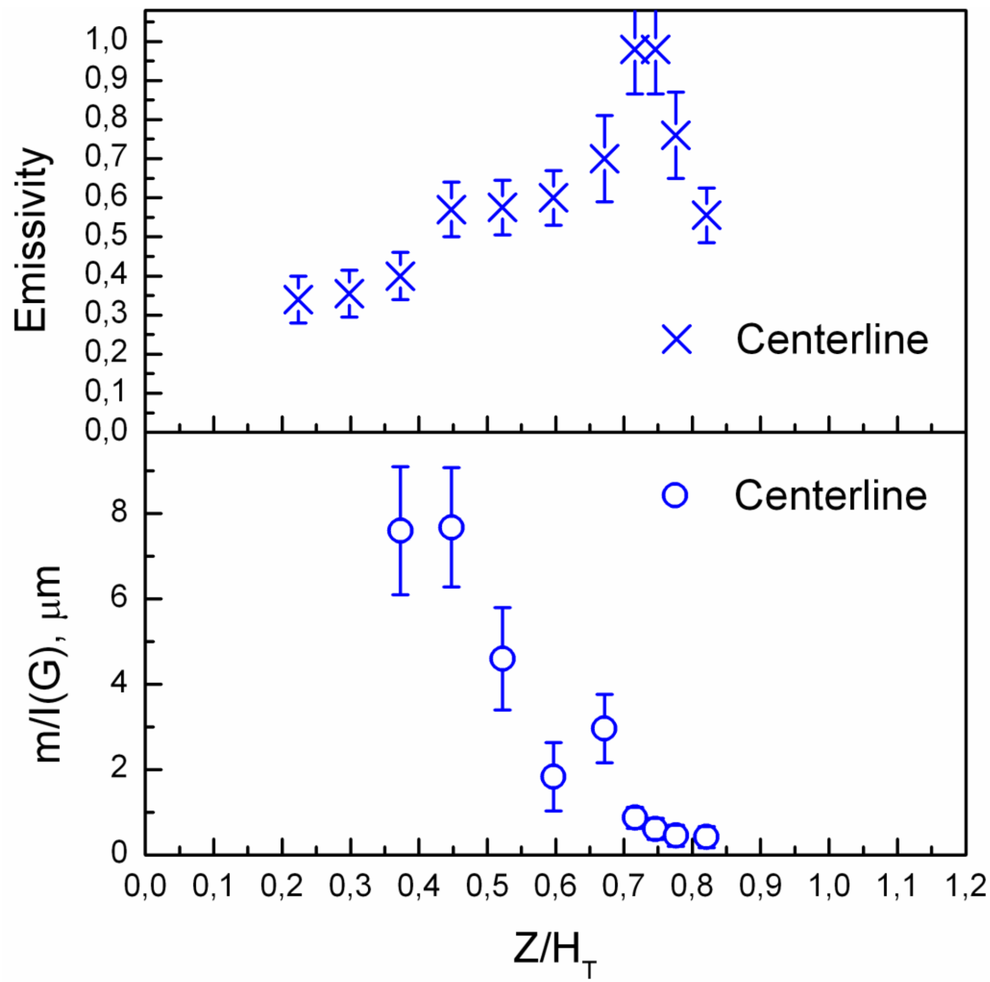

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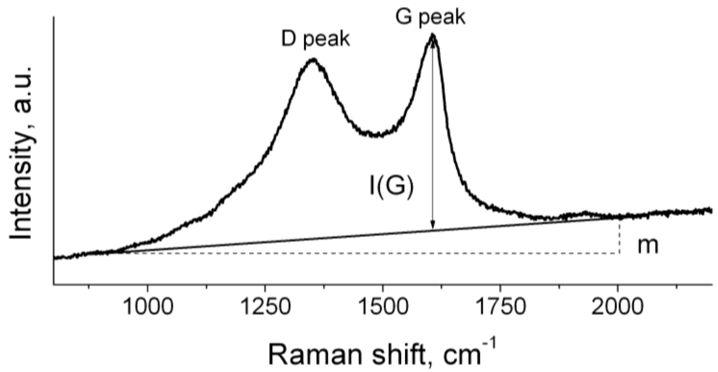

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Final Remarks /1

- A Thermophoretic-Thermocouple method based on TPD has been developed for the investigation of particle evolution in flame;
- The method here reported has the capability to measure simultaneously particle volume fraction and emissivity, being at the same time very simple, fast and cheap to operate;
- The method has been first successfully validated on a laminar premixed flame, and then applied for studying a laminar diffusion flame.

Final Remarks /2

❖ Precursor particles formed in the center of the flame have an emissivity ε~0.4-0.6 and can emit fluorescence;

❖ Emissivity of particles increases following a carbonation pathway up to ε~0.95, their capability to emit fluorescence strongly decreases and TPD-fv coincides with that measured by LII;

❖ In a moderately oxidative flame region, the inclusion of OH oxidation in the mass balance equation for TPD allows evaluating properly particle volume fraction.

THANK YOU FOR YOUR ATTENTION