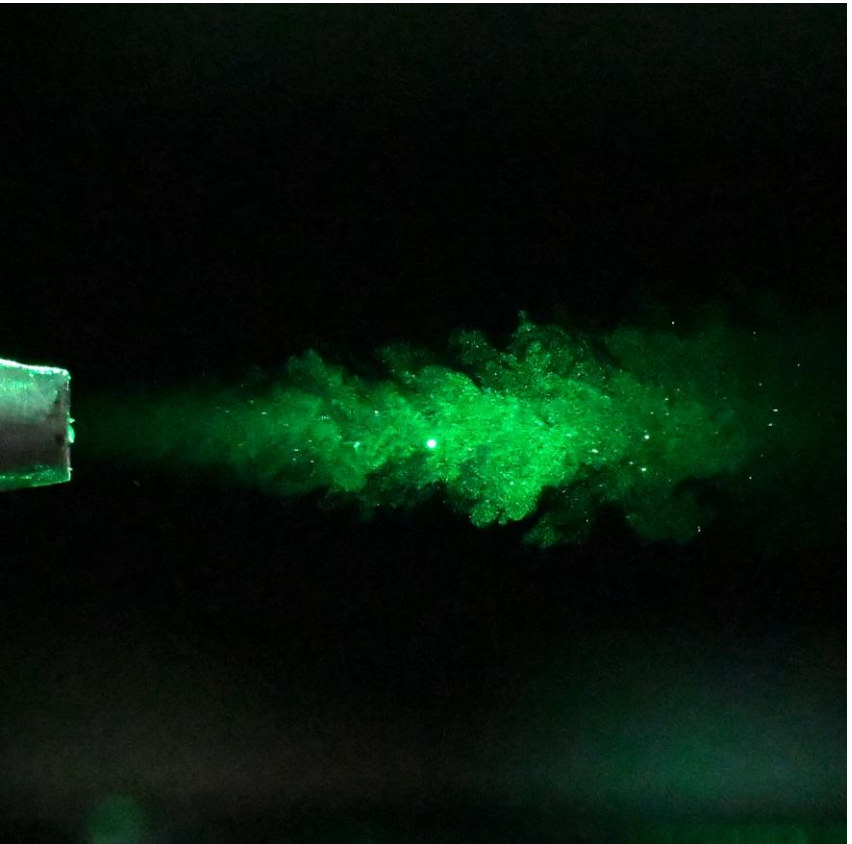
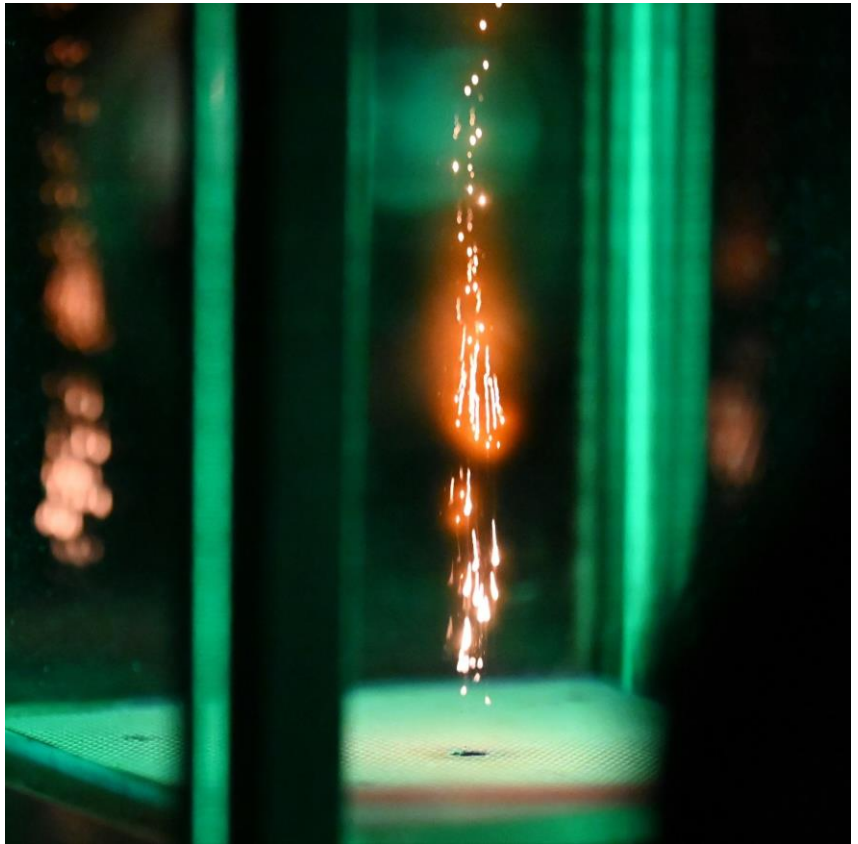
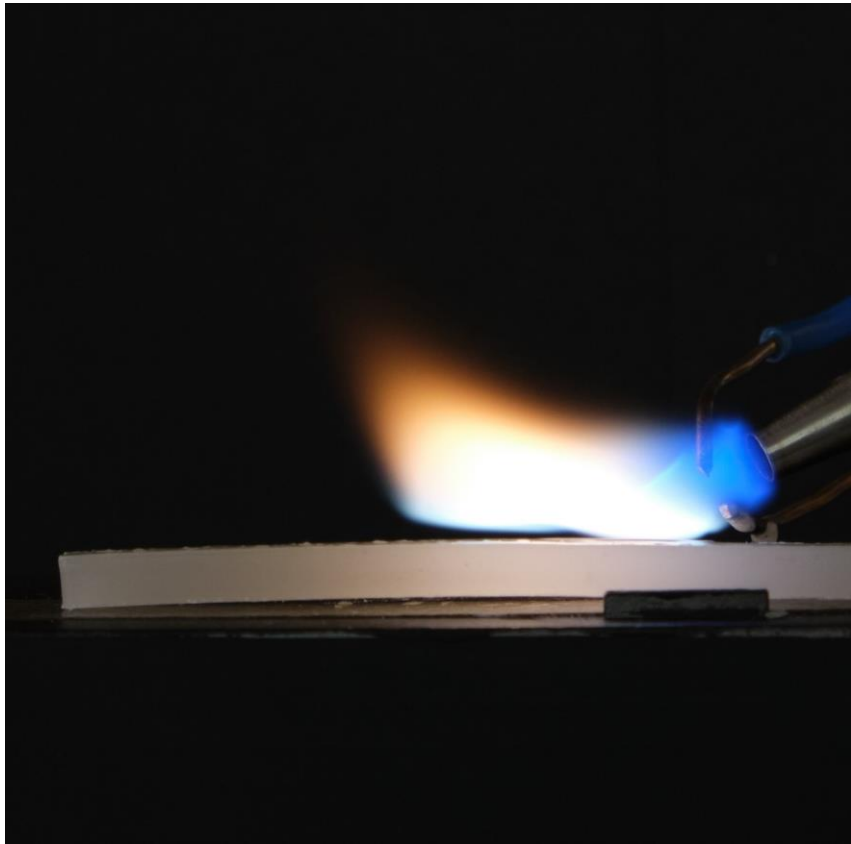
Optical diagnostics for carbonaceous solid fuels and flame retarded polymers in laminar and turbulent flows

Christopher Geschwindner

19th ERCOFTAC Da Vinci Competition – 10 Oct 2024







Solid fuels can be part of a sustainable future

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Coal-fired power plants produce 36% of electricity and **45% of CO_2 emissions** from power plants worldwide*

Phasing out coal-fired power generation is essential for achieving **climate targets**

Conversion of coal-fired power plants to CCUS technologies with biomass enables **negative CO_2 emissions**

Shutterstock

*International Energy Agency World Energy Outlook 2023

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Sustainable energy supply with solid fuels

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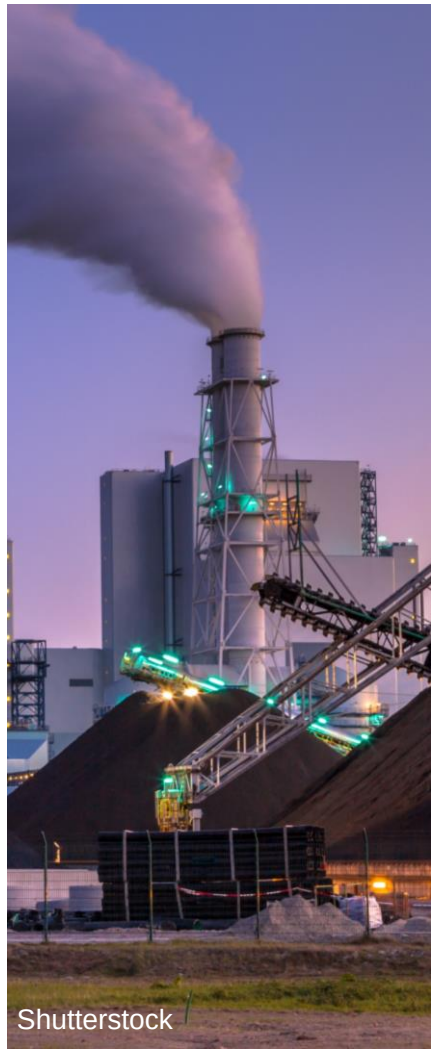
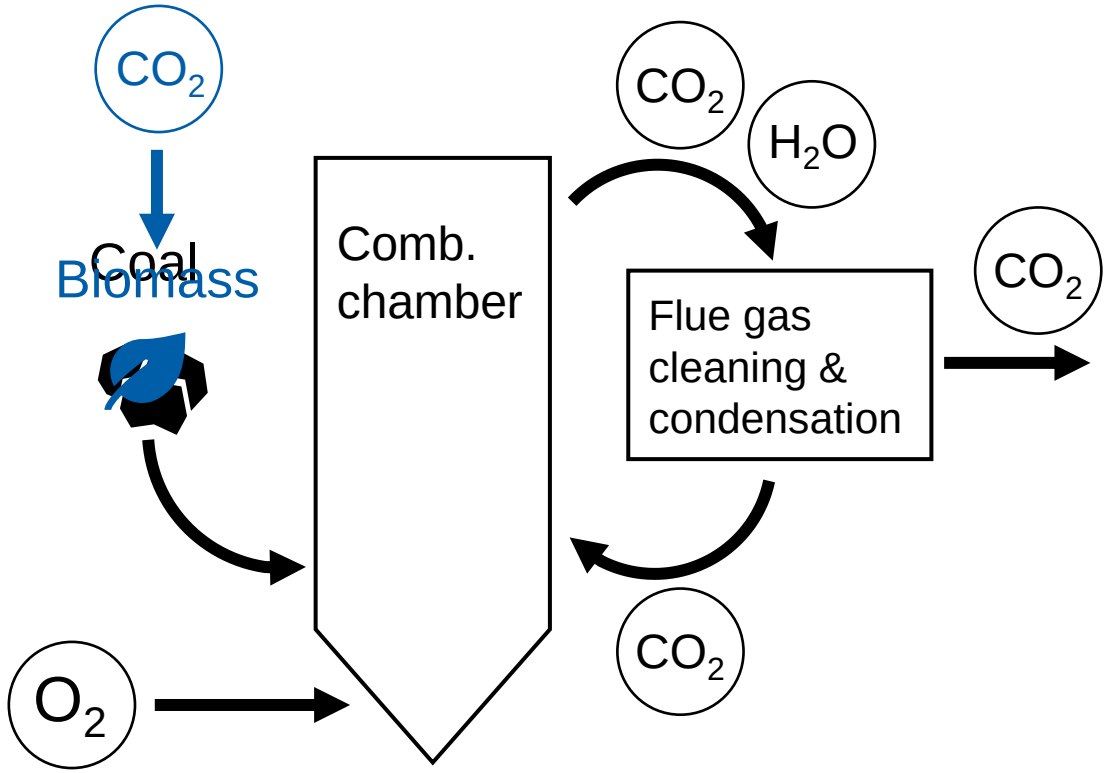

Shutterstock

*International Energy Agency World Energy Outlook 2023

Oxyfuel combustion of solid fuels



Adapted from
Li, T.; Geschwindner, C.; Dreizler, A.; Böhm, B. *Meas. Sci. Technol.* (2023)

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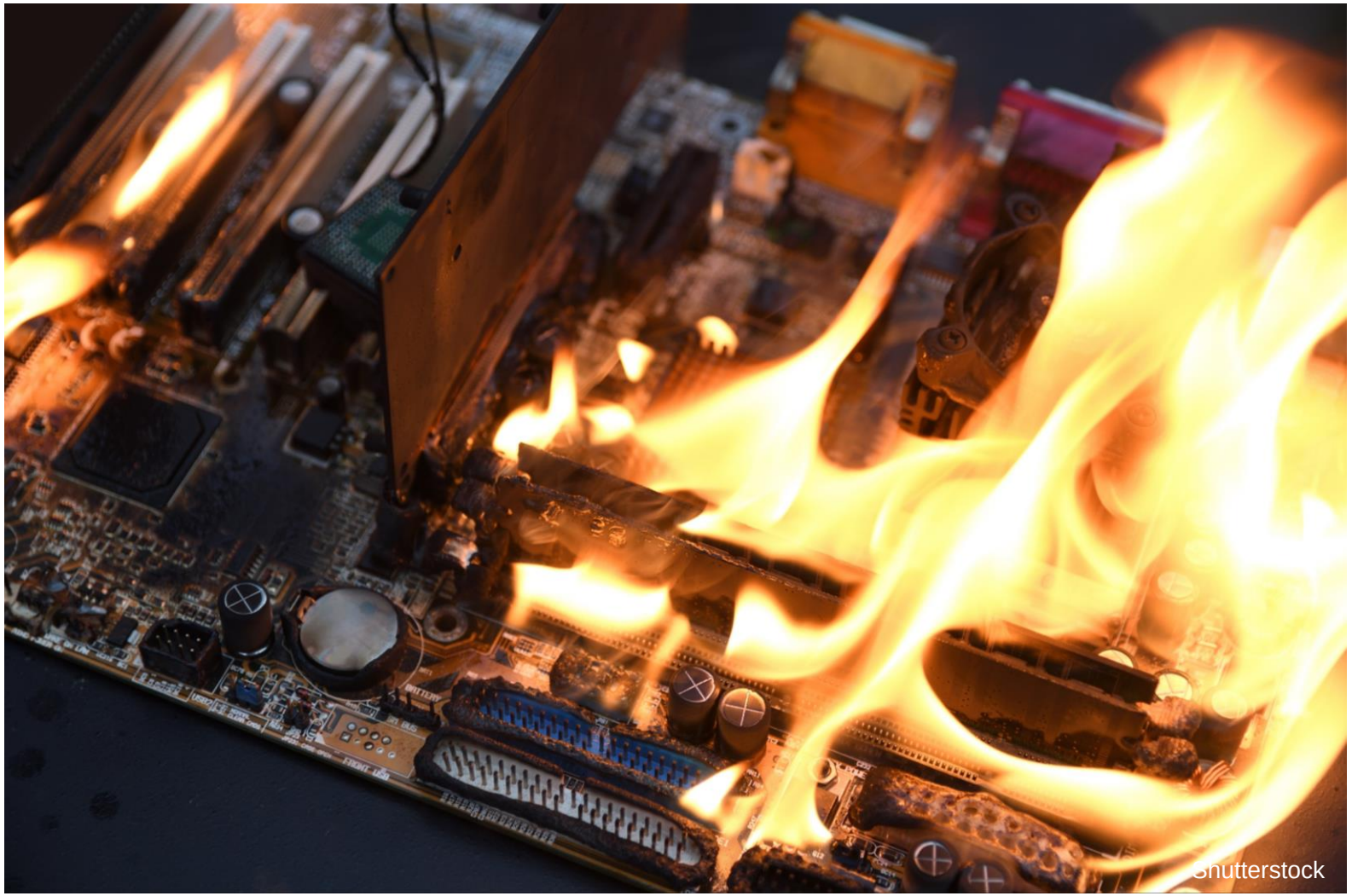
Effective flame retardancy for polymers

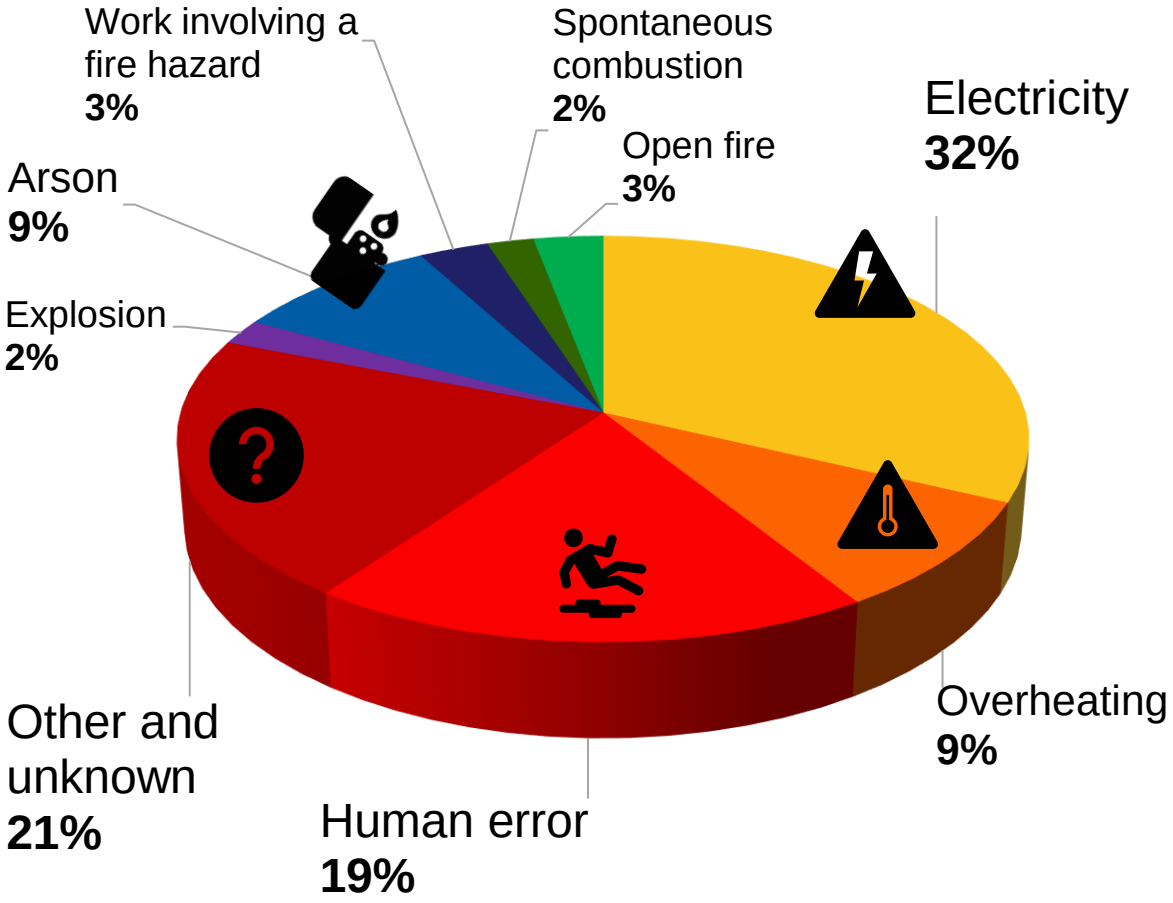


Polymer materials have replaced metals in many areas of industry

A crucial disadvantage of polymers is their **flammability**

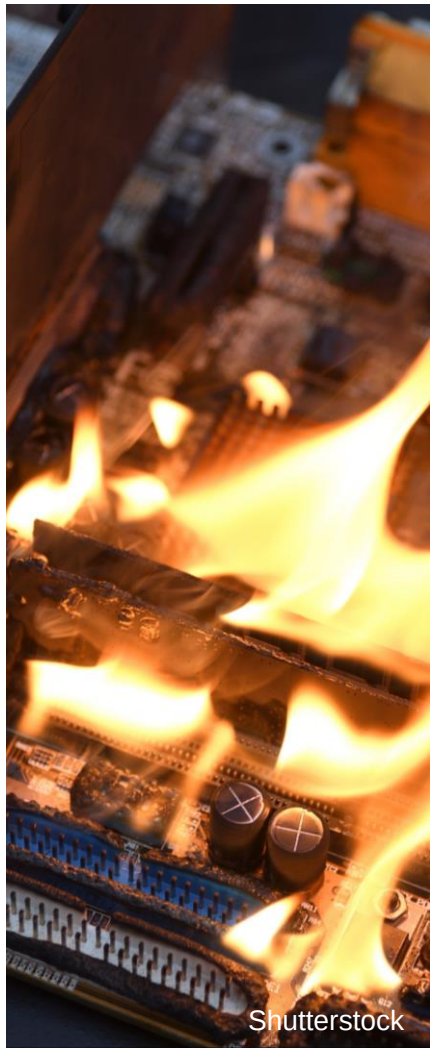
The use of effective **flame retardants** is necessary to prevent and slow down fires in safety-critical areas

Effective flame retardancy for polymers



Cause of fire statistics 2002-2022

Institute for Loss Prevention and Loss Research of the Public Insurance Companies (Germany)



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The combustion of solids is omnipresent

Which fundamental processes determine the combustion of solids?

Complexity of solid fuel combustion

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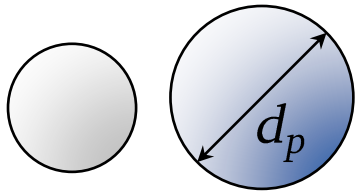
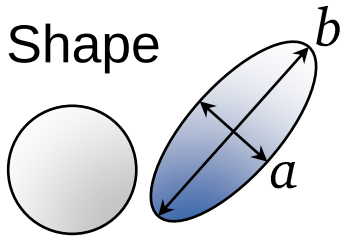
Individual aspects and their interaction

Solid phase

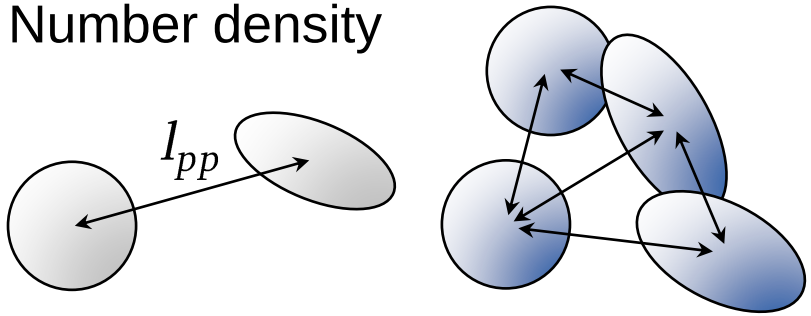
Size



Shape

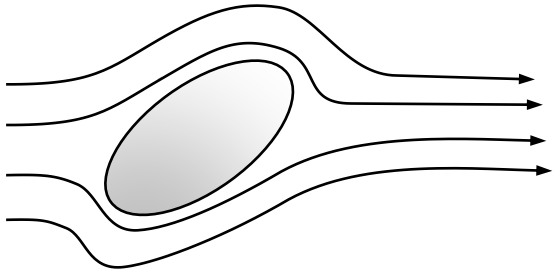


Number density

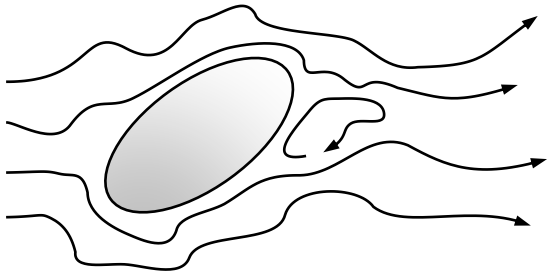


Flow field

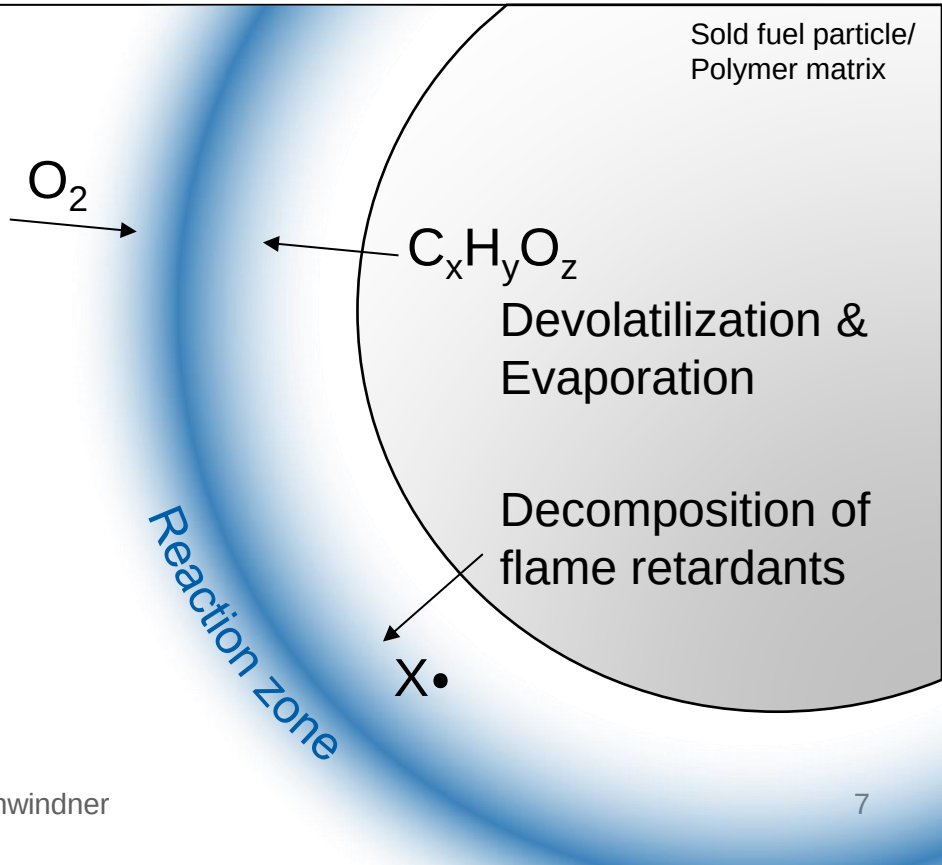
Laminar



Turbulent



Combustion



Complexity of solid fuel combustion

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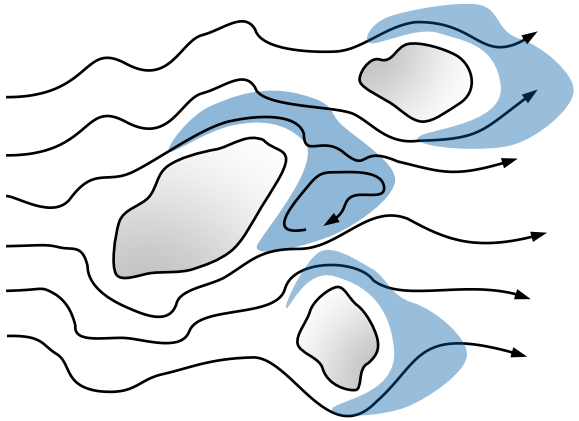
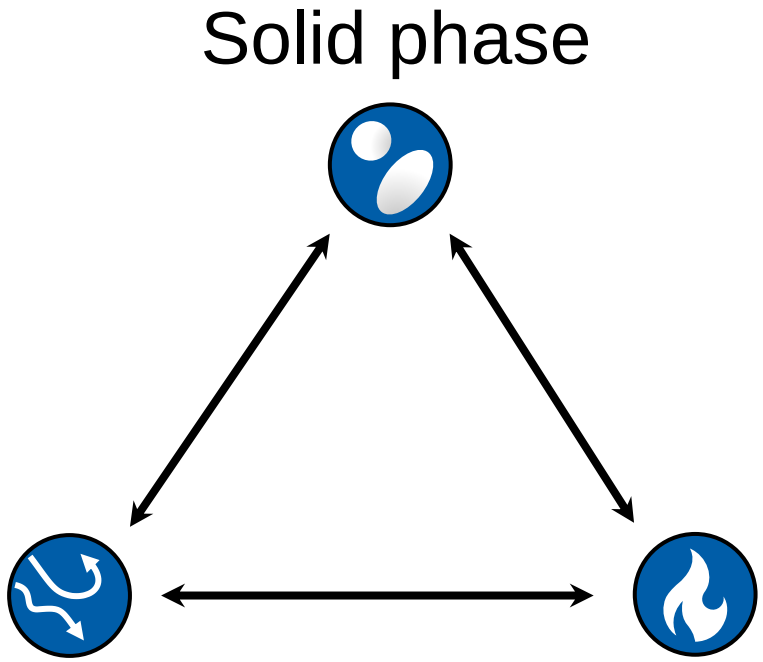
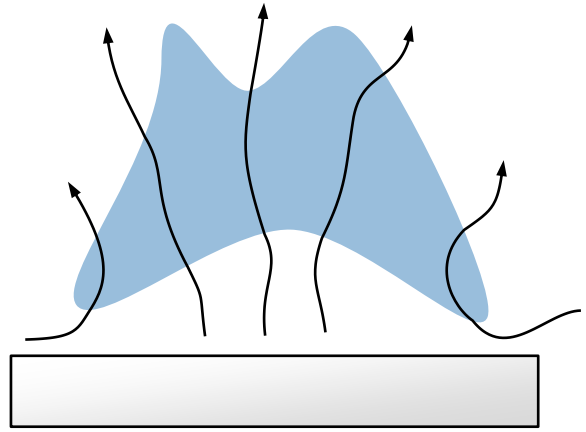
Turbulent dust flame





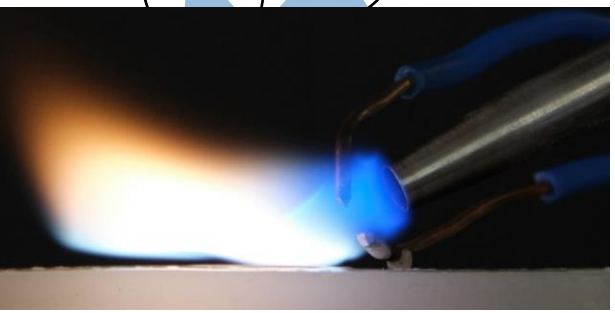
Burning polymer component



Overall objective of my PhD research

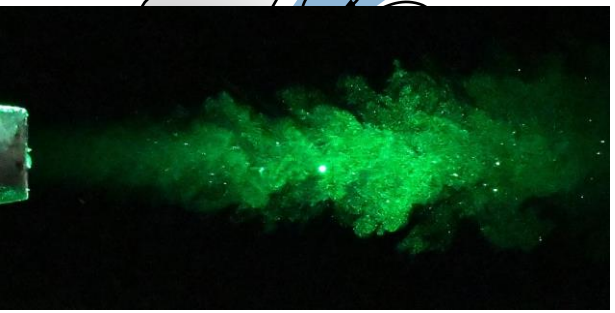
Development and application of experimental methods to characterize various aspects of the interaction of solid phase, flow and chemistry

Agenda: Research questions and approach



How do flame retardants affect the flammability of polypropylene?[1,2]

What role do oxyfuel atmosphere and particle-particle interactions play in the combustion of solid fuels?[3]



How can we capture aspherical biomass particles in detail within a turbulent jet?[4,5]

Optical Diagnostics

- ✓ *In-situ* applicability
- ✓ Minimally invasive
- ✓ High temporal and spatial resolution
- ✓ Possibility of simultaneous measurement of different variables (multi-parameter approach)

[1] Geschwindner et al. *Exp Fluids* 61 (2020)
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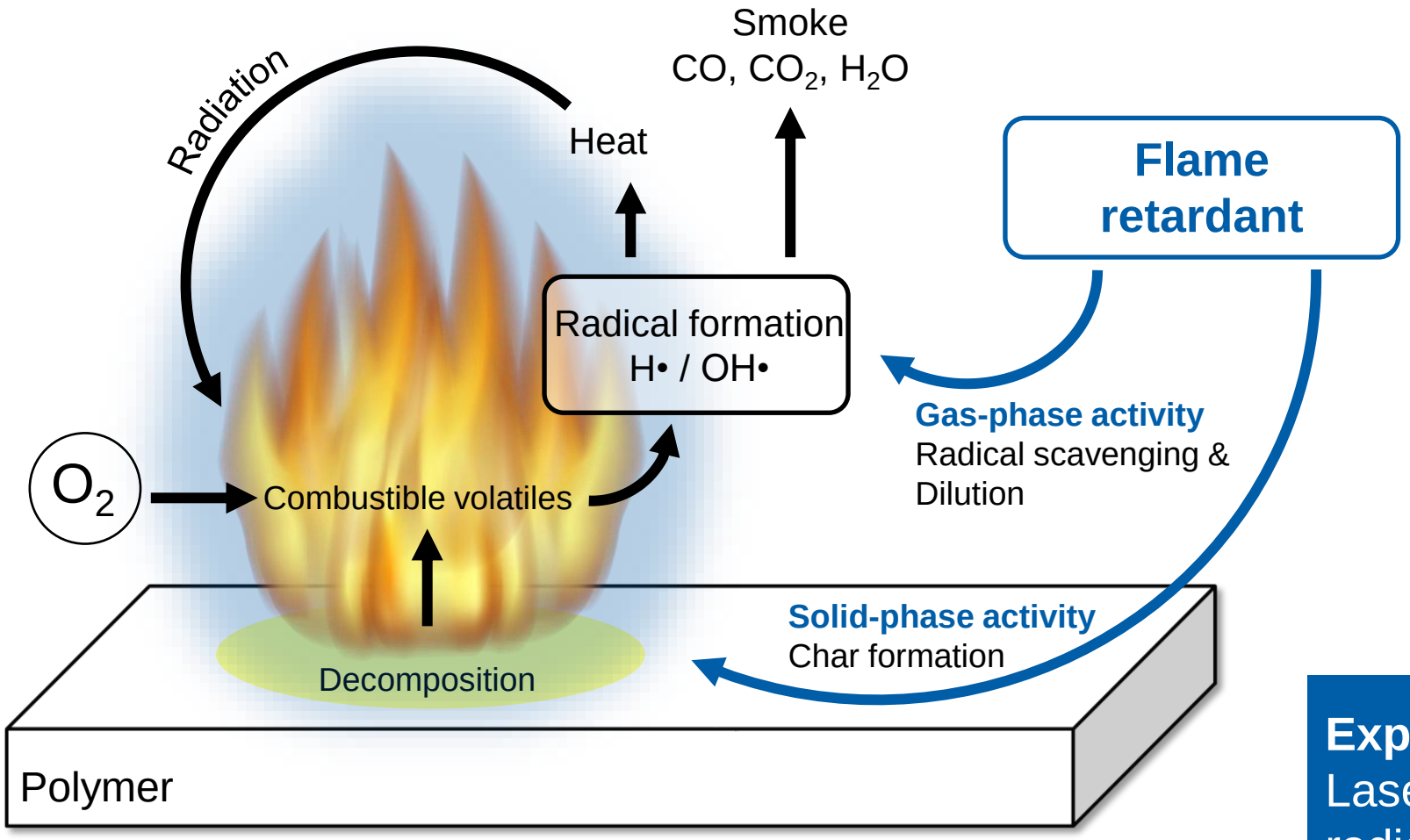
[5] Geschwindner et al. *Proc Combust Inst* 39 (2023)

How does a flame retardant work?



Velencoso et al. *Angew. Chem. Int. Ed.* 57, 10450-10467 (2018).

Chain branching

$H• + O_2 \rightarrow OH• + O•$

$O• + H_2 \rightarrow OH• + H•$

$OH• + CO \rightarrow CO_2 + H•$

Flame poisoning

$PO• + H• \rightarrow HPO$

$PO• + OH• \rightarrow HPO_2$

$HPO + H• \rightarrow H_2 + PO•$

$HPO + OH• \rightarrow PO• + H_2O$

Experimental approach
Laser-induced fluorescence of the OH radical to visualize radical scavenging

Experimental setup for particle studies

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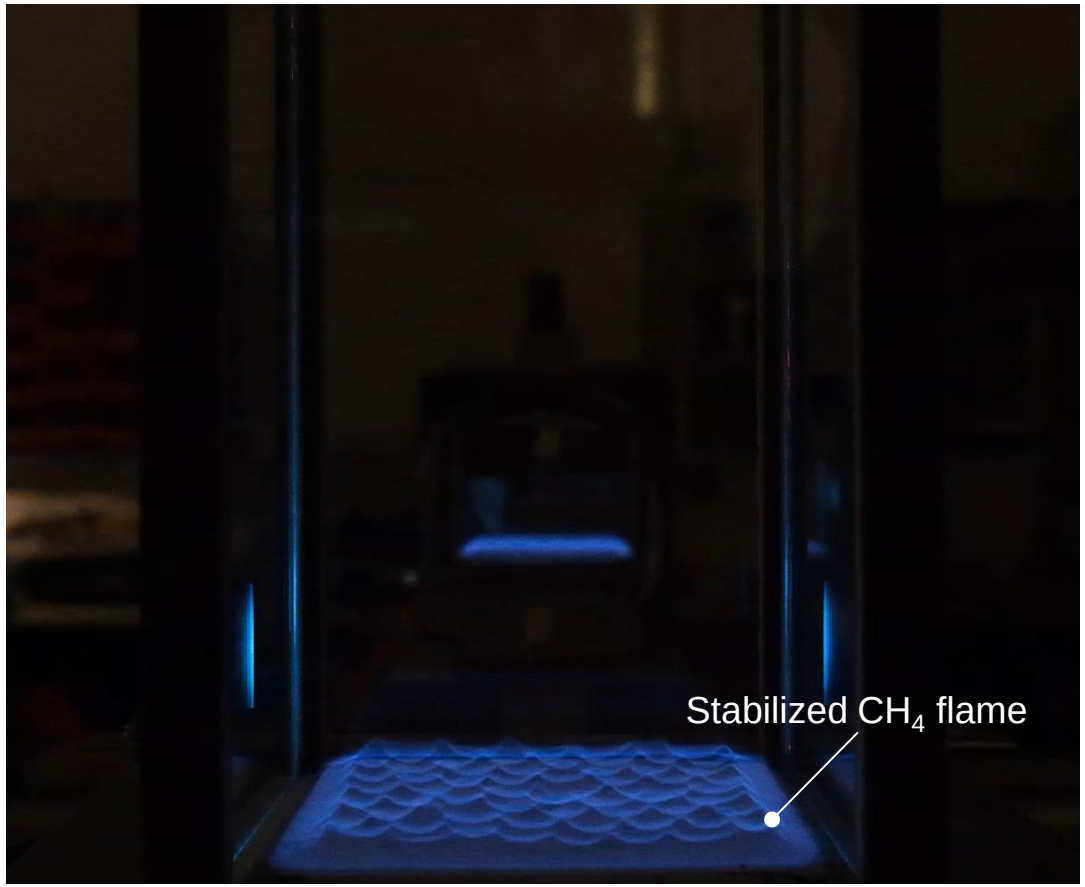
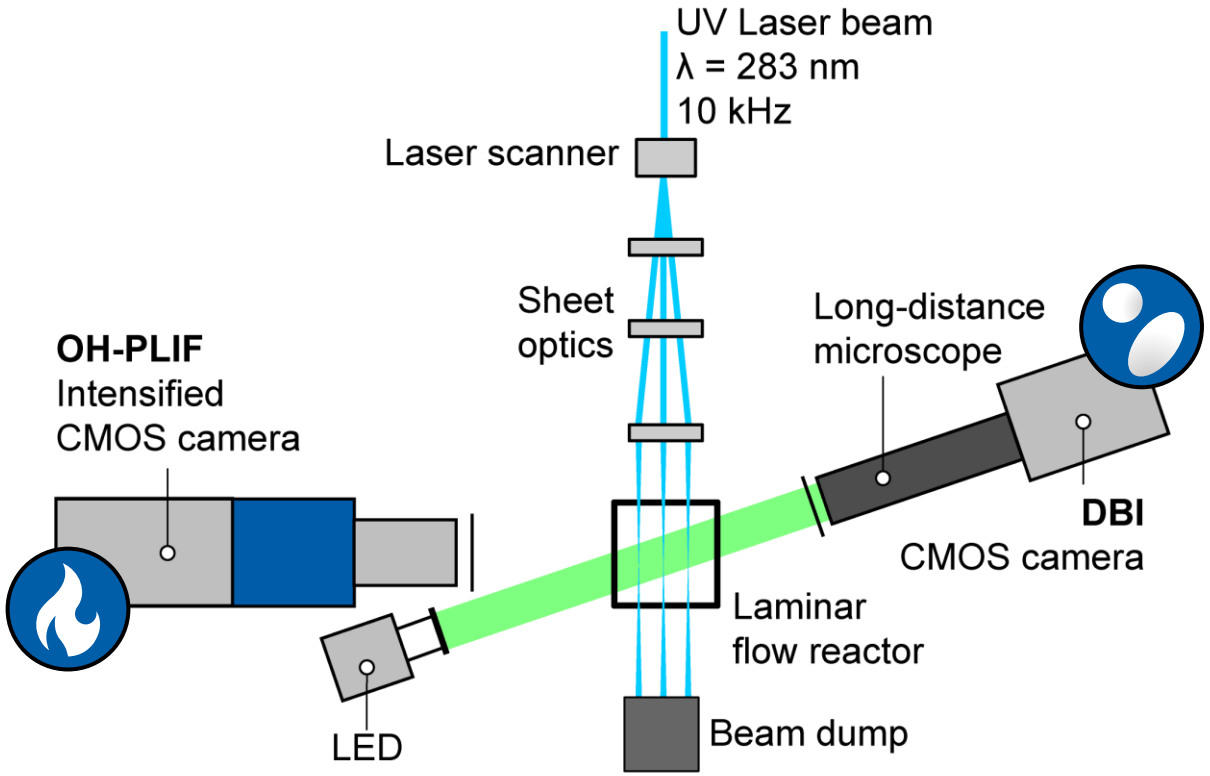
Multi-parameter measurement of flame and particles





Simultane Messung von Flamme und Partikel

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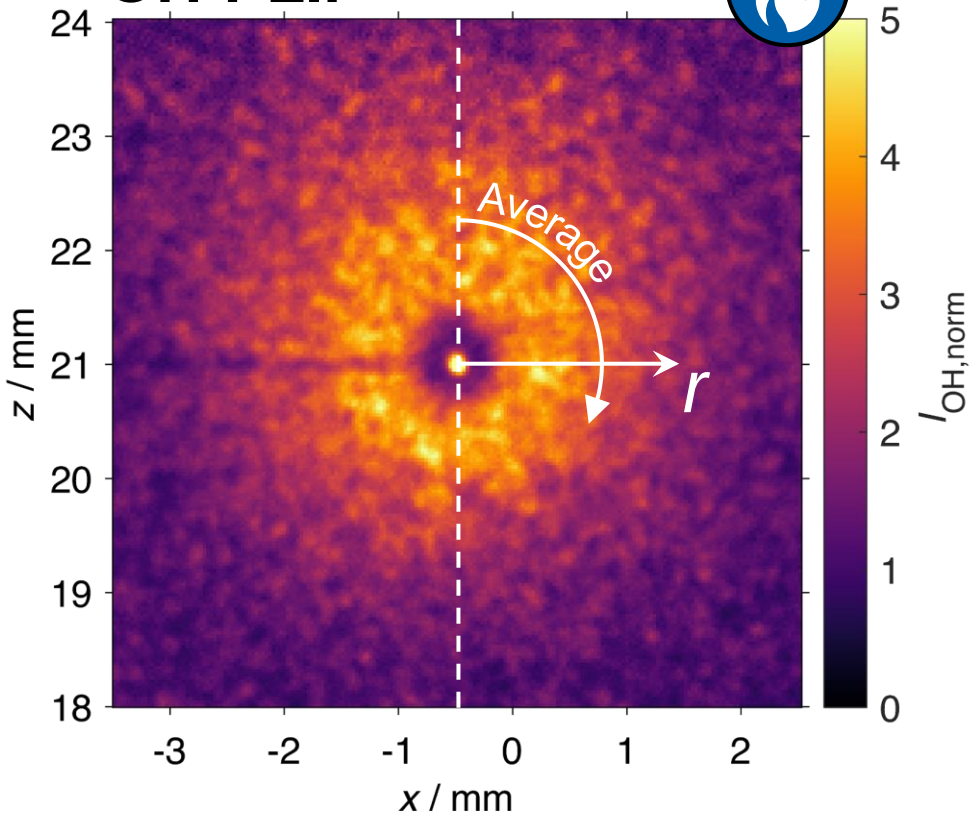
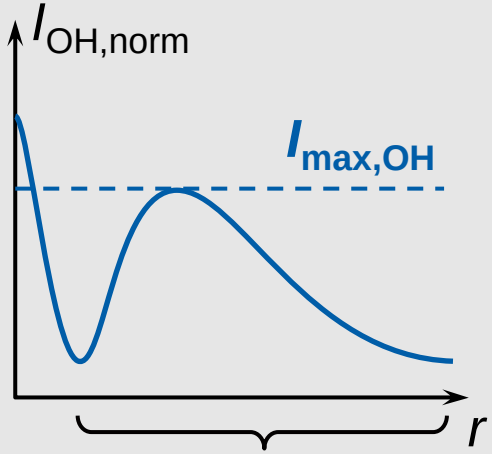
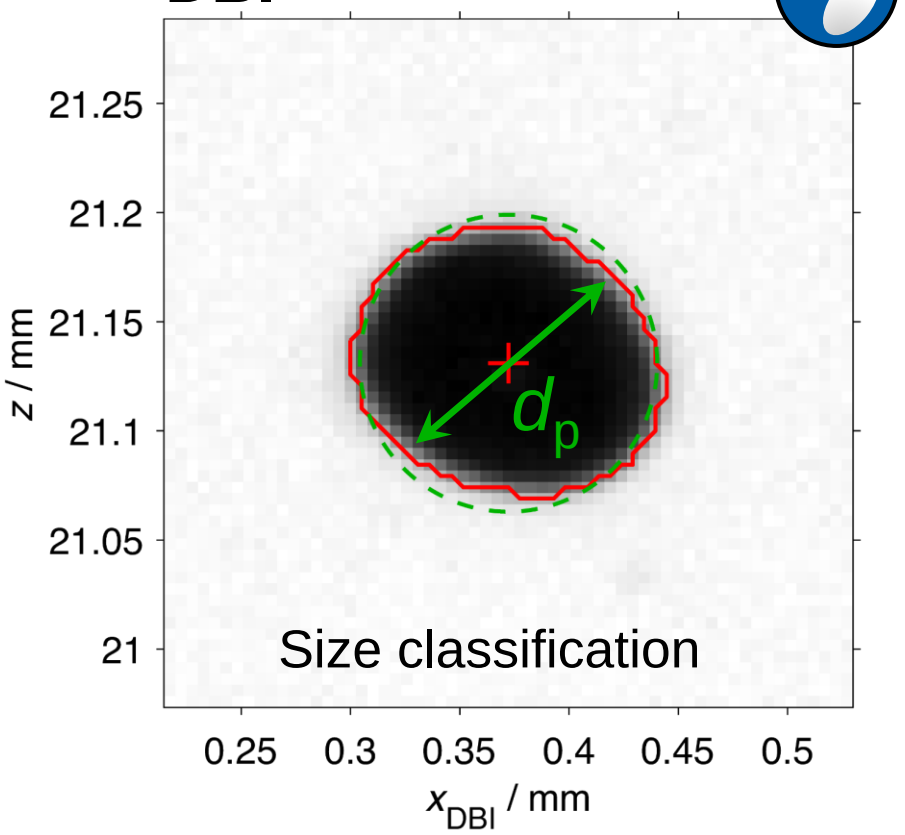
OH-PLIF



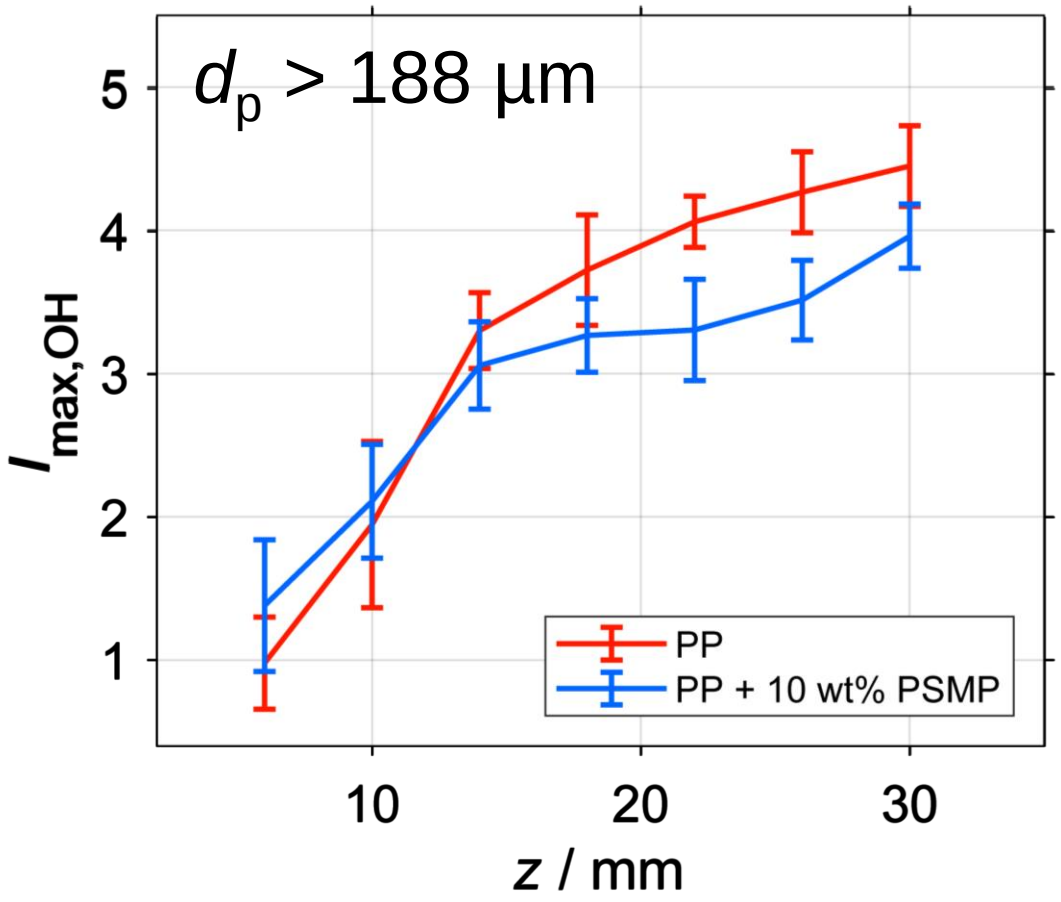
Mean radial OH fluorescence signal



DBI



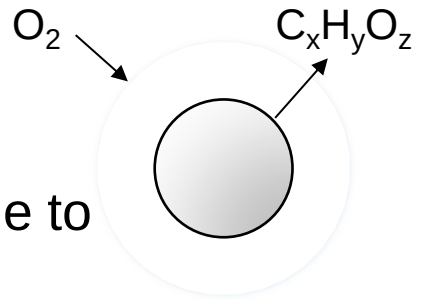
Gas-phase activity in the fully developed flame

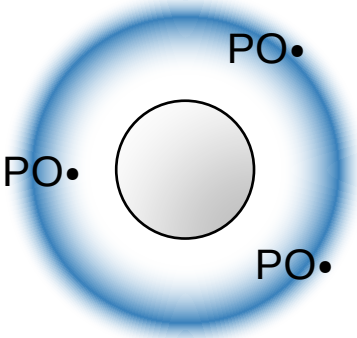


Ignition phase

Peak OH signal increases sharply due to **high heating rates** of the particles

Small difference between neat and flame-retardant polymer

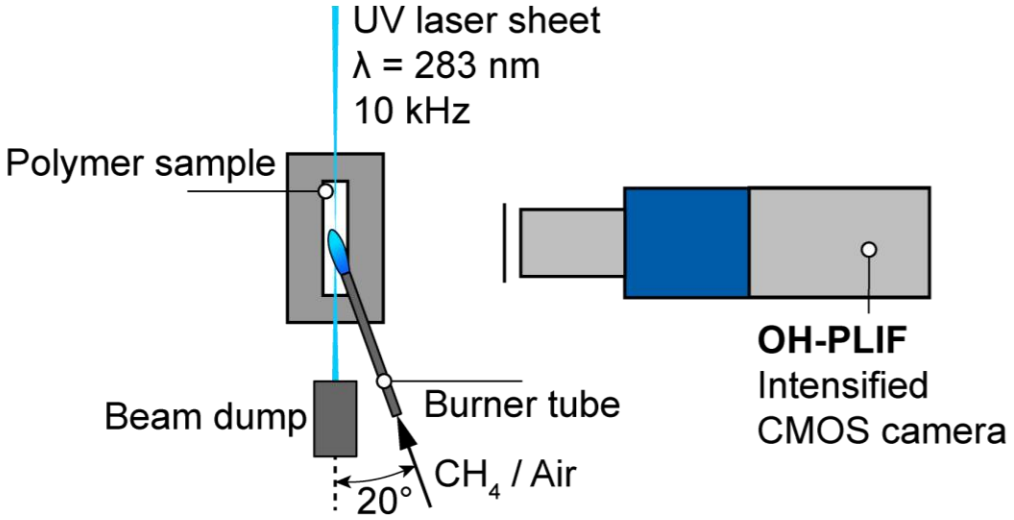


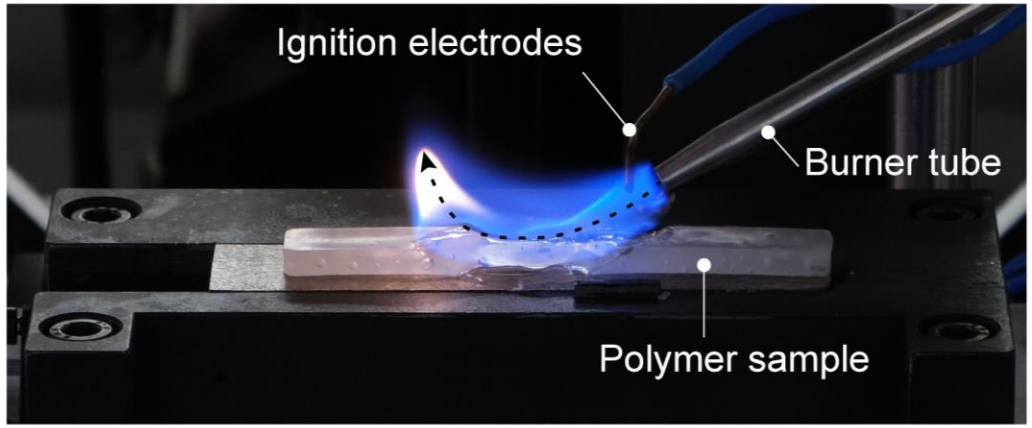


Spherically developed flame

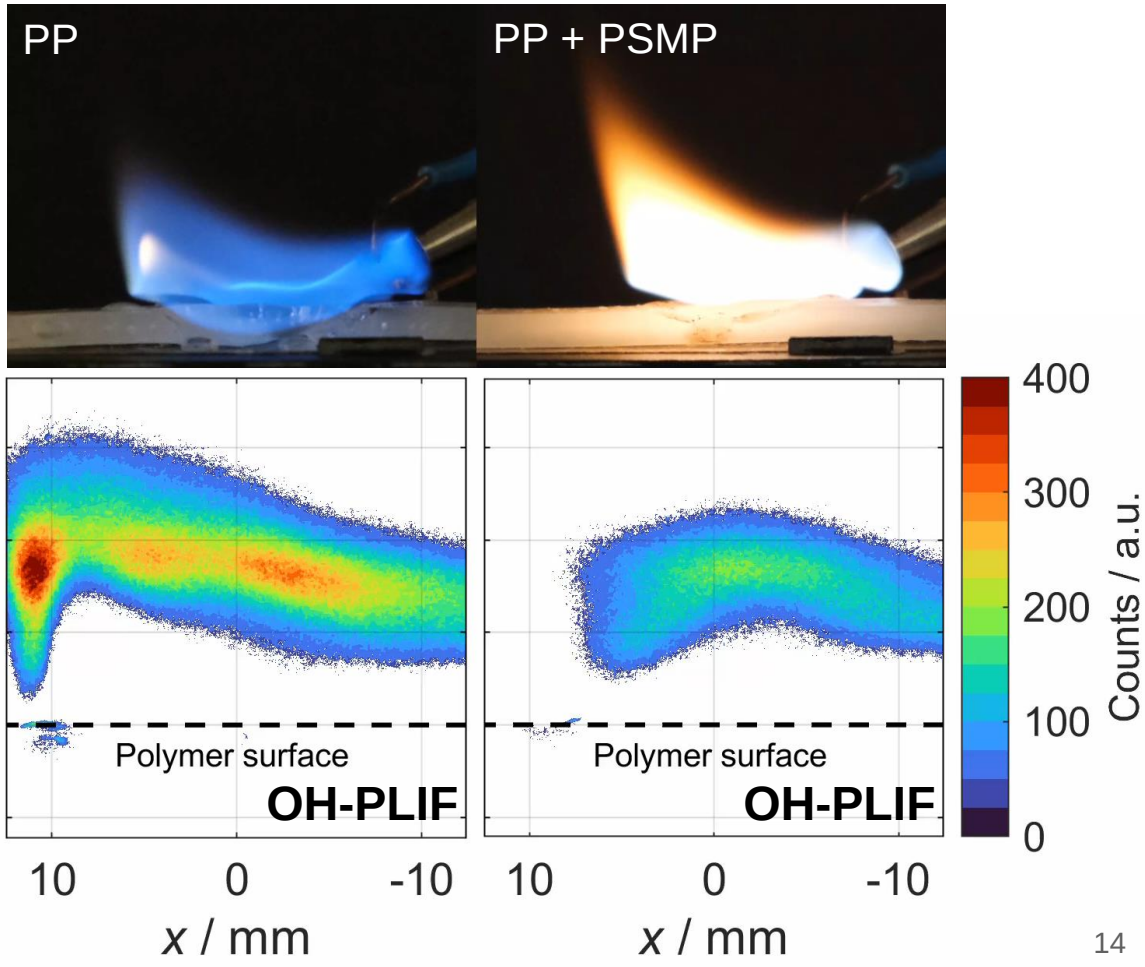
OH signal for PP + PSMP branches off from neat PP, indicating **gas-phase activity**

Adapted burning test for larger samples





Extinction of external flame after 60 s



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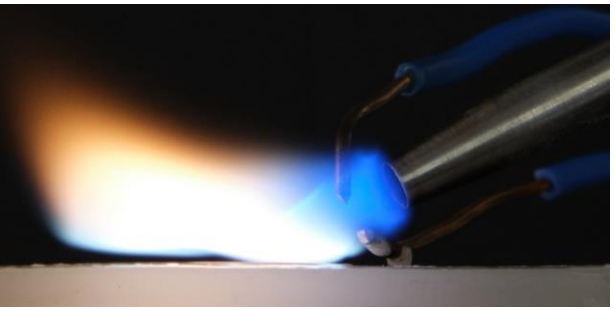

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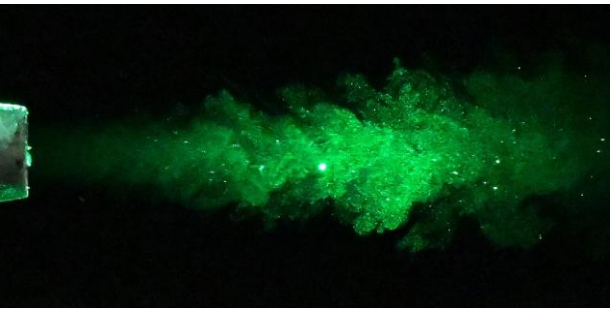

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Turbulent biomass-laden jet flows

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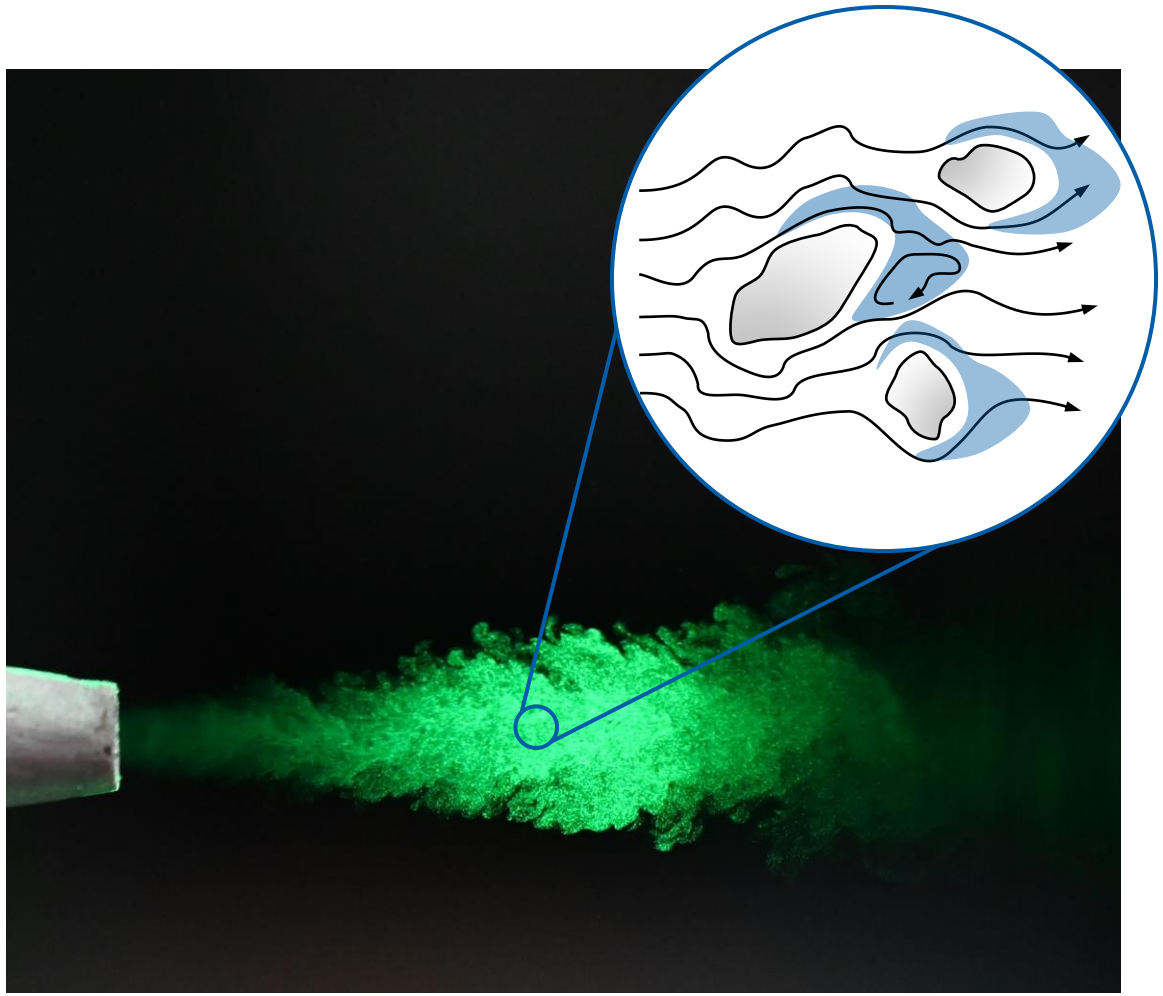

Turbulent flows cover a wide range of temporal and spatial scales

Flow measurements require a high temporal and spatial **dynamic range**

Accurate characterization of multiphase flows requires **simultaneous determination** of carrier and dispersed phase

Relative velocity Particle size

$$Re_p = \frac{\overbrace{|\vec{u} - \vec{u}_p|}^{\text{Relative velocity}} \overbrace{d_p}^{\text{Particle size}}}{\nu}$$

Experimental setup for ultra-high-speed diagnostics

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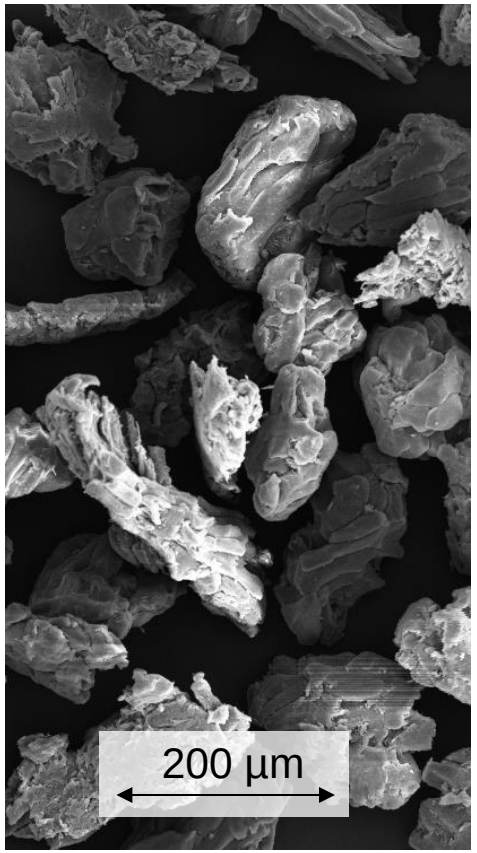
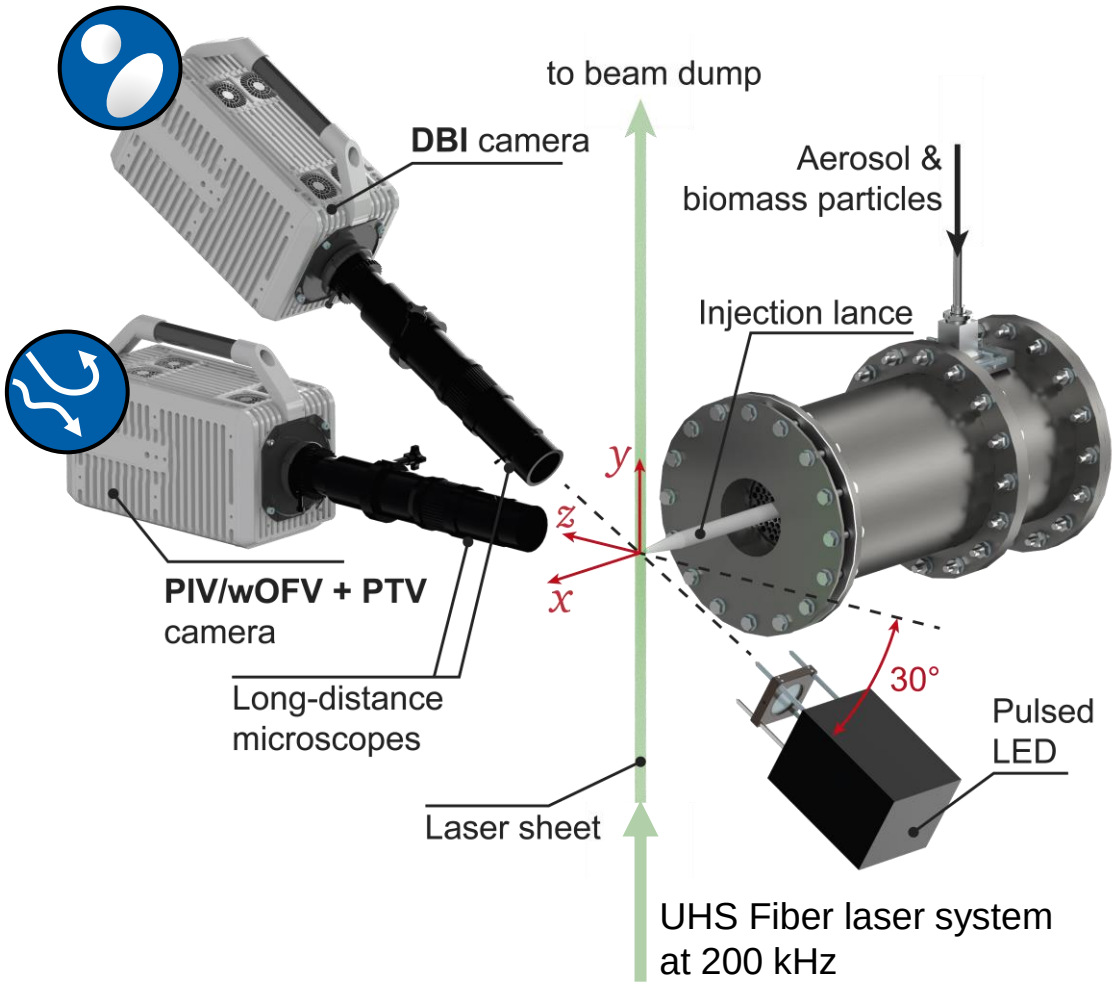
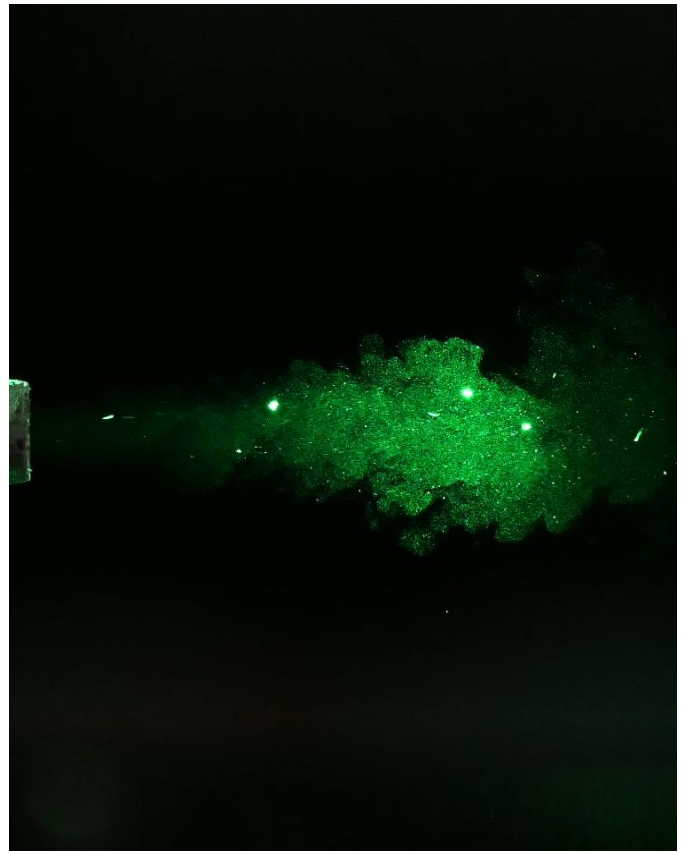
Walnut shells



Average aspect ratio 1.59
Exit Stokes number: 860



UHS Fiber laser system
at 200 kHz



Particle-turbulence interaction at 200 kHz

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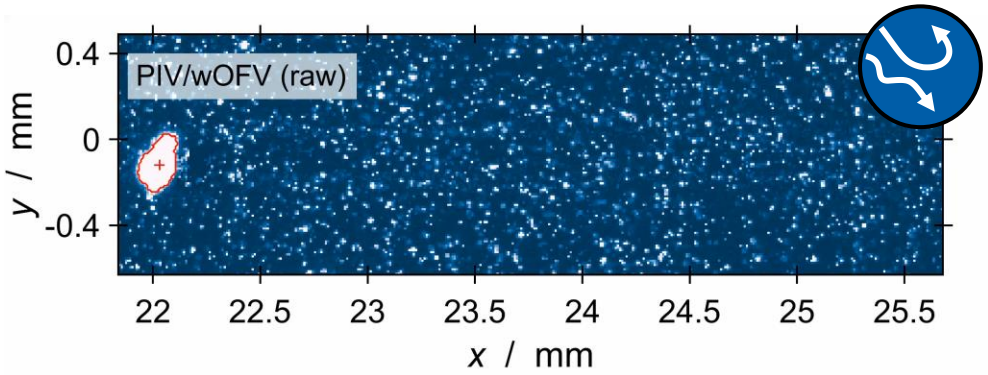
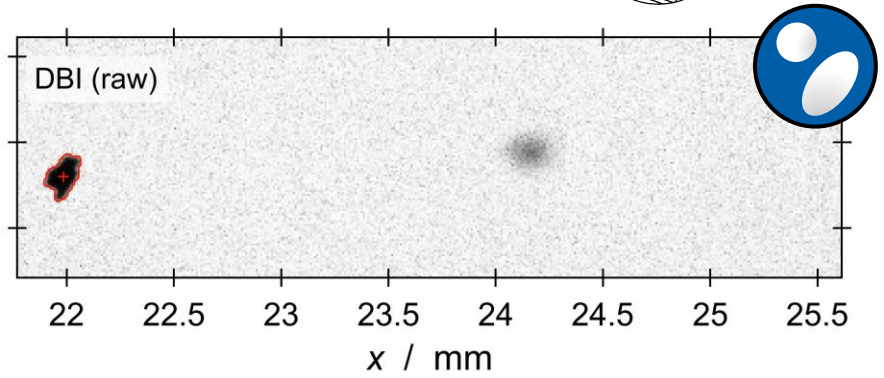
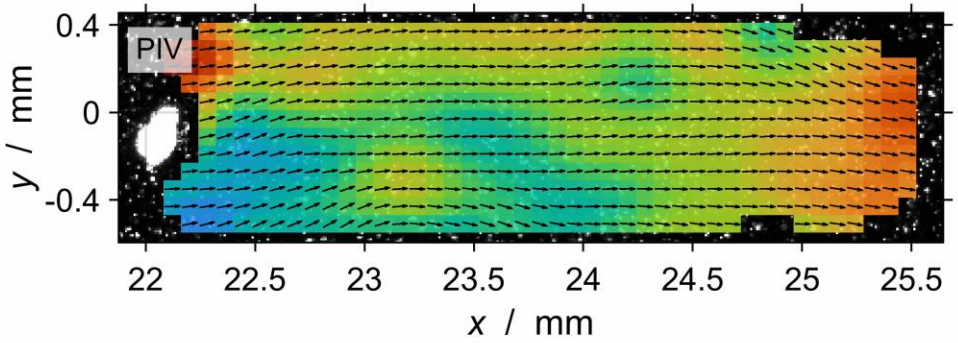
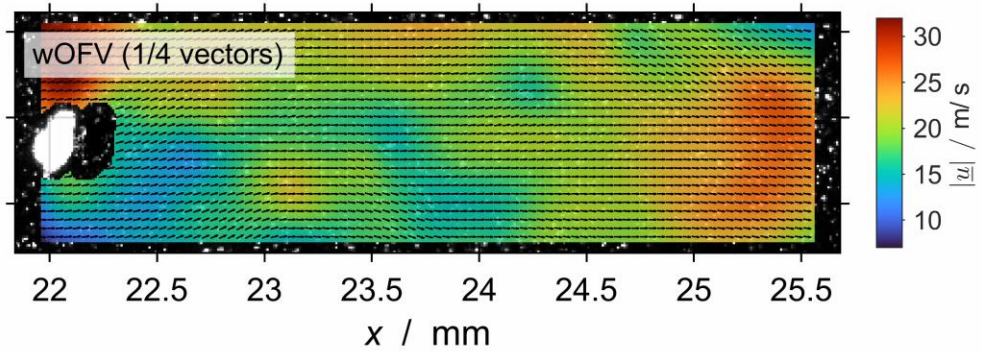
Raw images





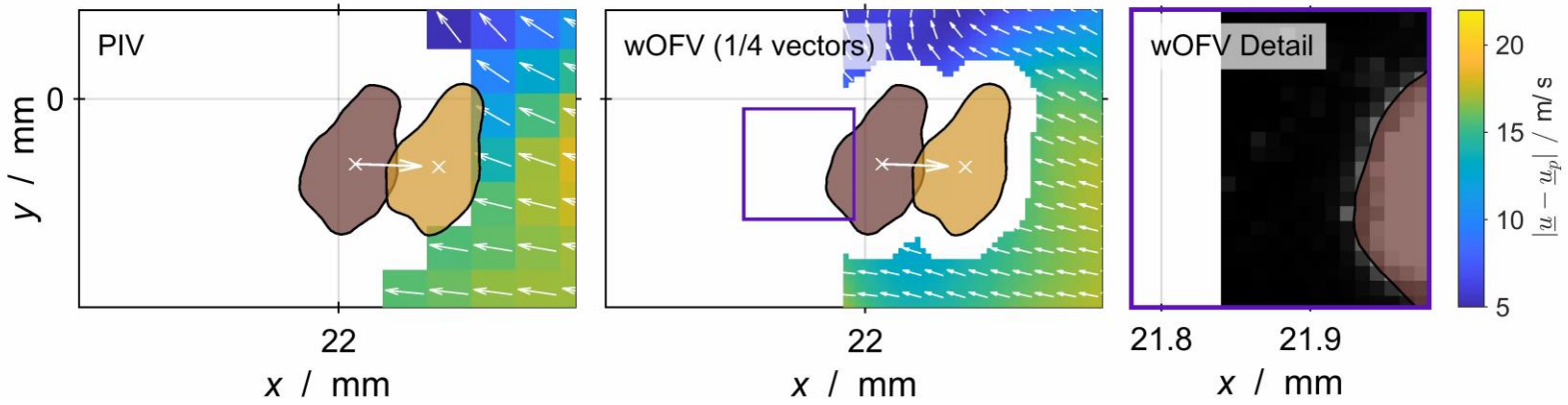
Flow velocimetry





Relative velocity field

$$Re_p = \frac{\overbrace{|\vec{u} - \vec{u}_p|}\, d_p}{\nu}$$



$$Re_{p,\mathrm{wOFV}} = 154.6$$

$$Re_{p,\mathrm{PIV}} = 142.9$$

$$t = 0\ \mu\mathrm{s}$$

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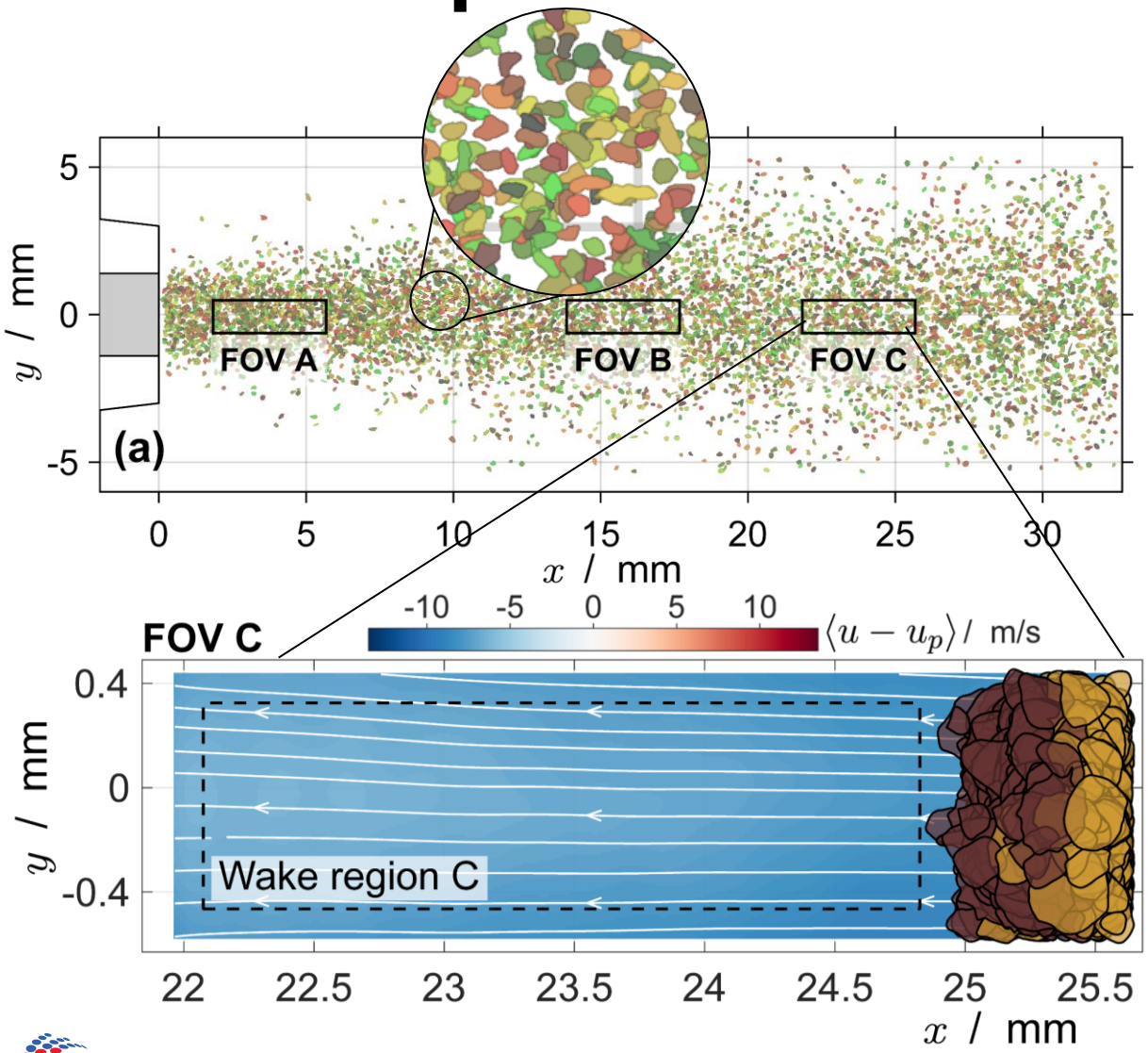
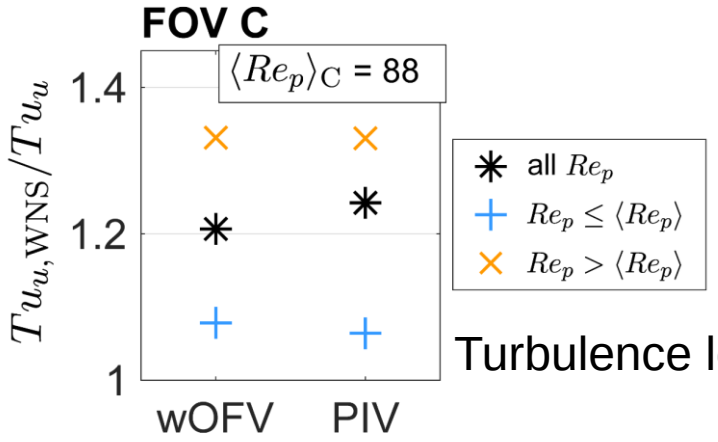
Particle-specific turbulent wake analysis



High spatio-temporal resolution and multi-parameter approach enables a particle-specific turbulence level analysis

Larger turbulence level increase for PIV is attributed to its low-pass filtering characteristics, while wOFV resolved smaller scales in the carrier phase turbulence



Turbulence level change

Optical diagnostics for solids combustion research

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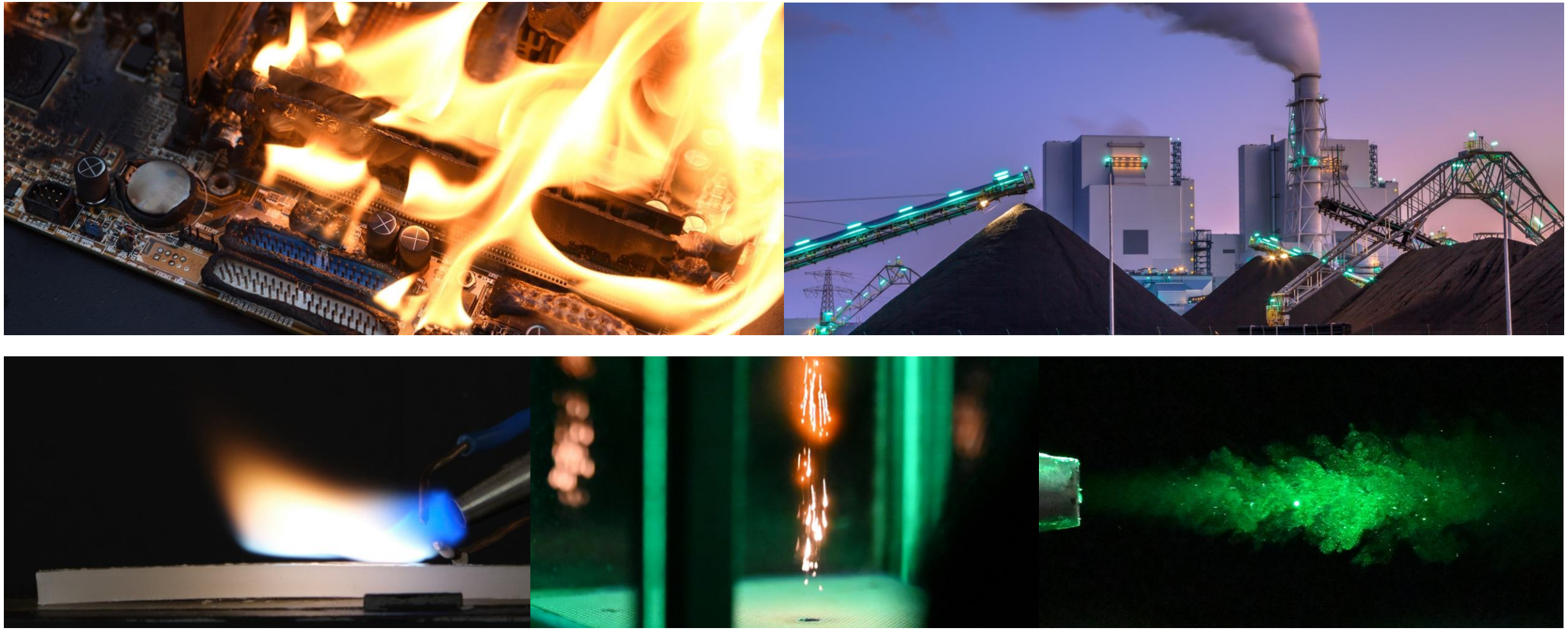
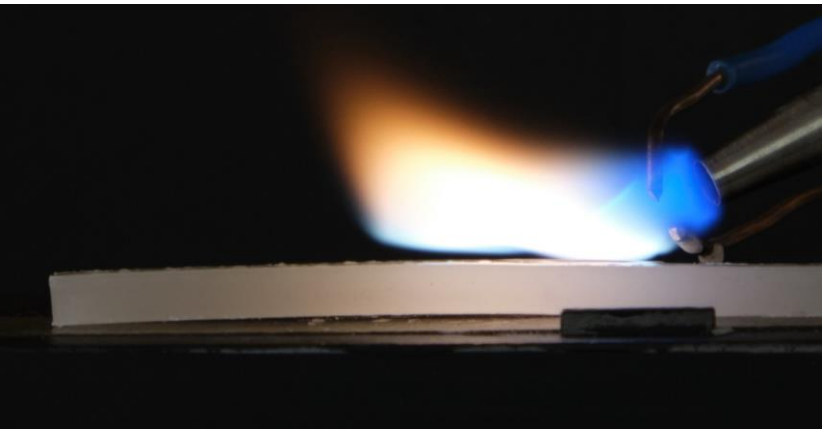
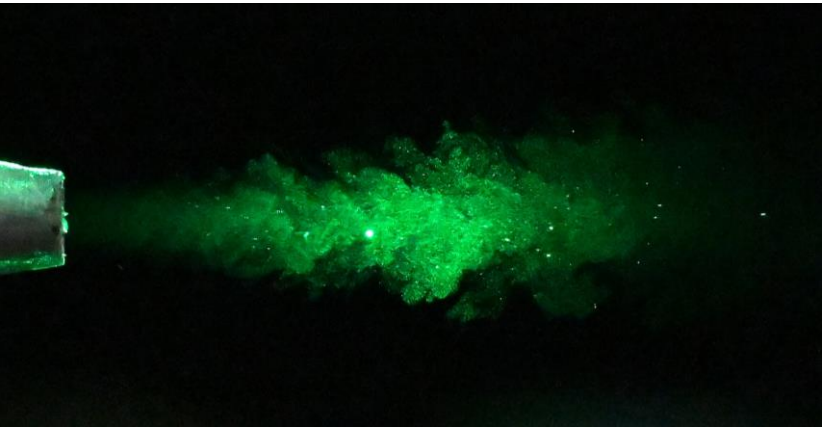


Summary and main outcome

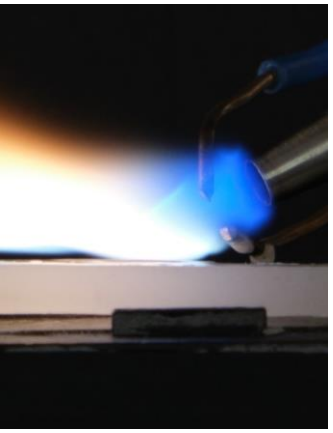


Optical diagnostics can characterize gas-phase activity of flame retardants in polypropylene, extending previously used chemical decomposition analysis



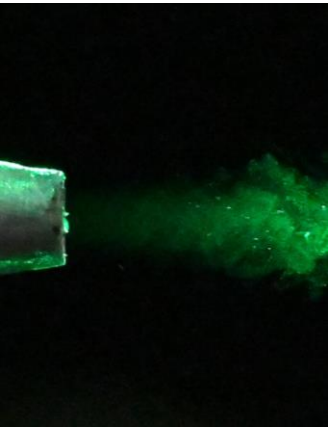
Biomass-turbulence interaction was investigated down to the particle scale using ultra-high-speed velocity measurements with unprecedented spatio-temporal resolution

Outlook and future research



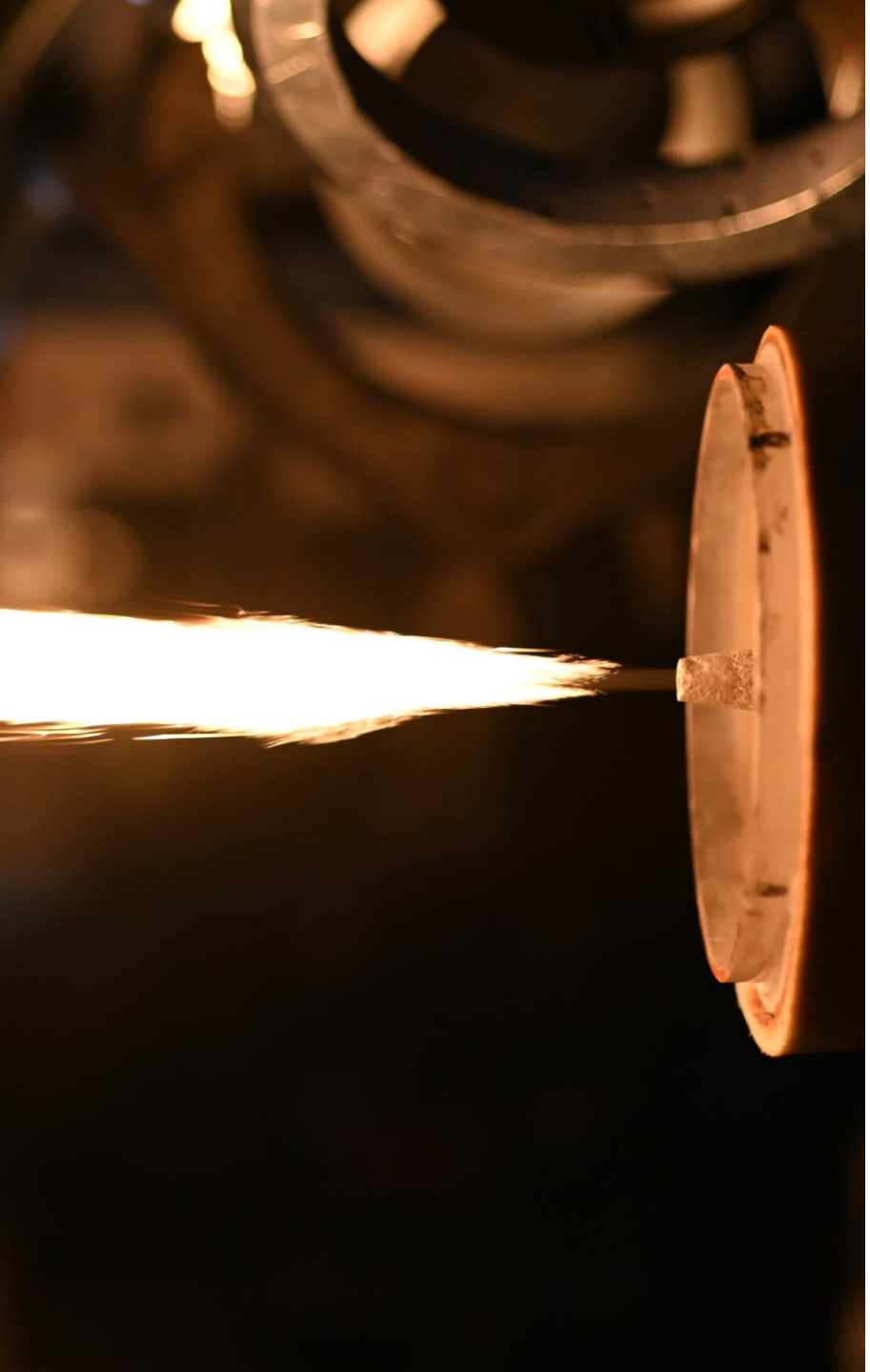
Optical diagnostics can characterize gas-phase activity of flame retardants in polypropylene, extending previously used chemical decomposition analysis

→ Combining findings from polymer chemistry and fire safety for the **predictive design** of flame retardants



Biomass-turbulence interaction was investigated down to the particle scale using ultra-high-speed velocity measurements with unprecedented spatio-temporal resolution

→ Particle-resolved investigation of **turbulent solid fuel flames** including biomass and metal fuels



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