UNIVERSITÄT
DUISBURG
ESSEN

Offen im Denken

Experimentelle und numerische Untersuchung von verdampfenden Flüssigfilmen

Institute for Combustion and Gas Dynamics
Reactive Fluids

PaREGEn

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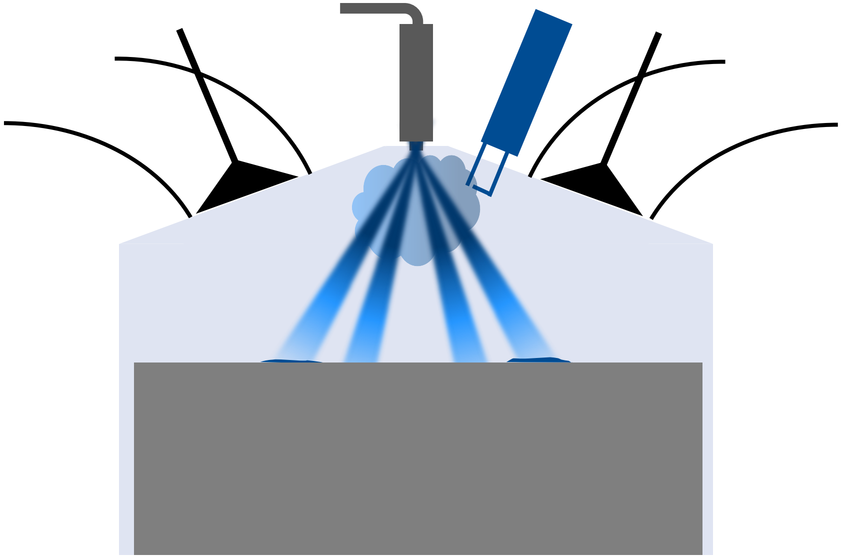
Duisburg, 01.10.2019

Motivation

- High fuel efficiency and suppression of knock in gasoline direct-injection engines (DISI) but emission of **ultrafine soot particles**

- Fuel injection early in the cycle leads to a homogeneous fuel/air-mixture at ignition timing but also to the formation of **fuel films**
  - Evaporating fuel films on the piston surface
  - Pool fire fed by liquid fuel-films on the piston (**diffusion flame**)[1]



➥ **Laser diagnostics to image fuel-film evaporation, soot precursors, soot**

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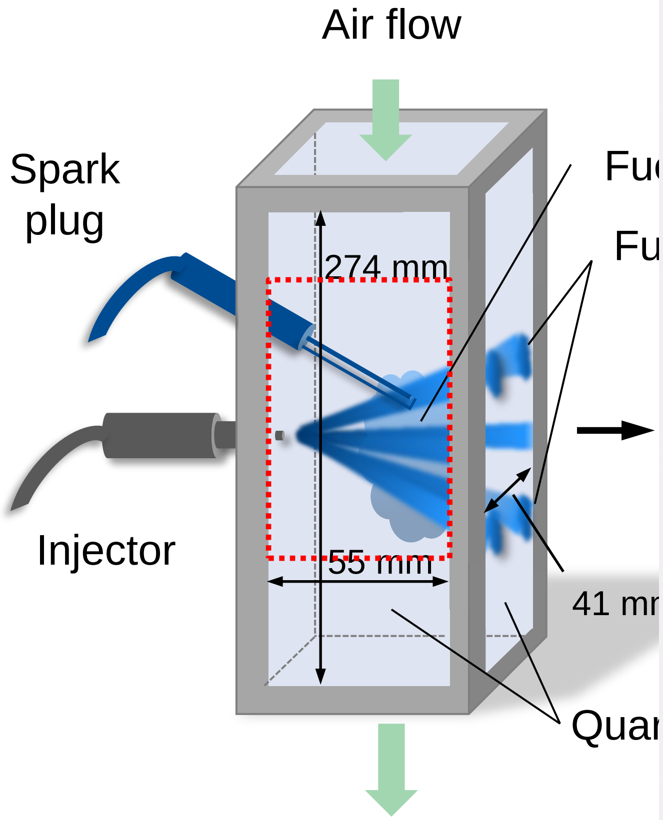
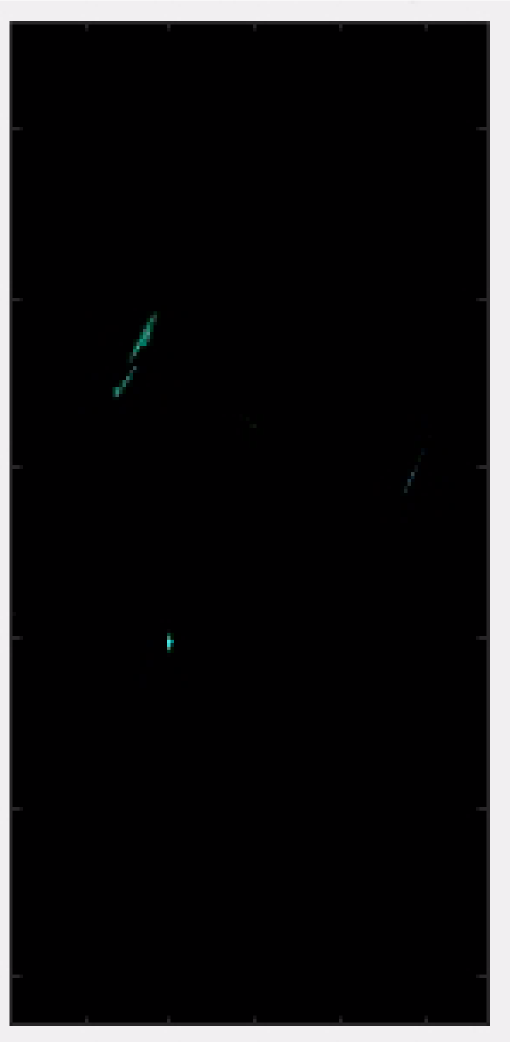
[1] Stojkovic, B.D., Fansler, T.D., Drake, M.C., and Sick, V., *Proceedings of the Combustion Institute* 30(2):2657-2665, 2005.

Experiment

Wind tunnel with opti

est section





	Iso-octane + toluene
ocity	1.83 m/s
ature	381 K
e	352 K
rature	361 K
essure	100 bar
ure	1 bar
ass	4.3 mg

of the fuel/air-mixture is
after end of injection

Fuel-film thickness imaging

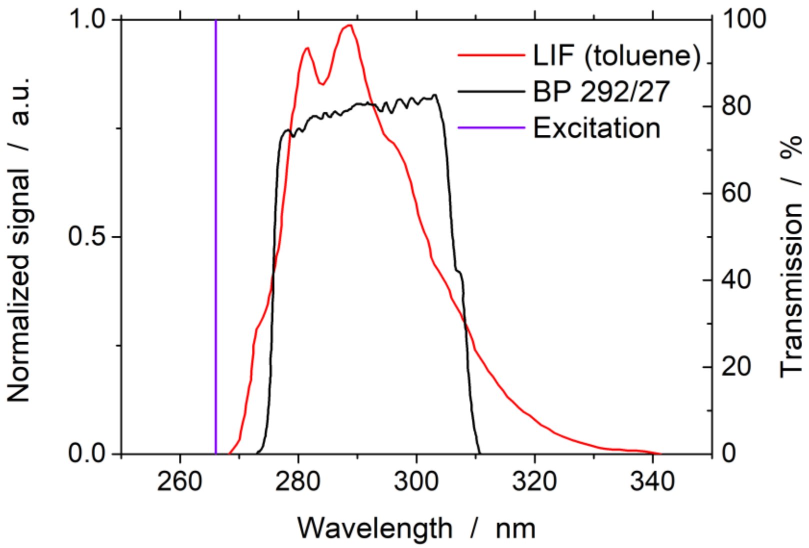
Tracer laser-induced fluorescence (LIF)

- Adding known amount of fluorescing species to non-fluorescing surrogate => **Similar phyiscal properties** and **known photophysical properties of tracer**

$$I_{\mathrm{LIF}} = \phi \cdot \Omega \cdot \eta \cdot I_0 \cdot \left(1 - e^{-\varepsilon^* c \boxed{d}}\right)$$

$$I_{\mathrm{LIF}} = \phi \cdot \Omega \cdot \eta \cdot I_0 \cdot \varepsilon^* \cdot c \cdot \boxed{d}$$

I_0	Incident intensity	ε^*	Extinction coefficient
ϕ	Fluorescence quantum yield	c	Concentration
η	Detection efficiency	d	Absorption path length
Ω	Collection efficiency		



- Other techniques for fuel-film thickness imaging
  - Refractive Index matching (< 3 µm)[2]
  - Laser Absorption Spectroscopy

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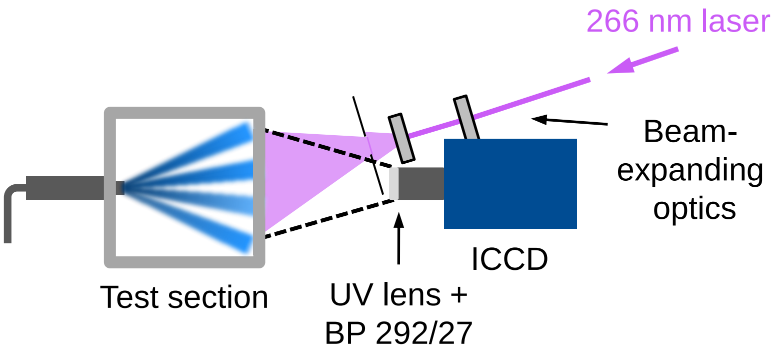
[2] Drake, M.C., Fansler, T.D., Solomon, A.S., and Szekely, G., "Piston fuel films as a source of smoke and hydrocarbon emissions from a wall-controlled spark-ignited direct-injection engine," SAE Technical Paper 2003-01-0547, 2003.

Fuel-film imaging

Optical layout and calibration



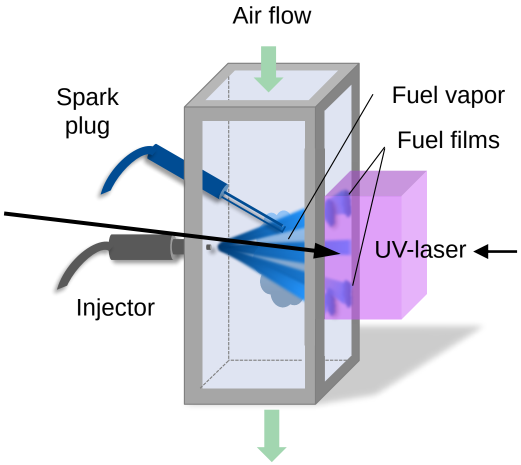
266 nm laser

Beam-expanding optics

ICCD

Test section

UV lens +
BP 292/27



Air flow

Spark plug

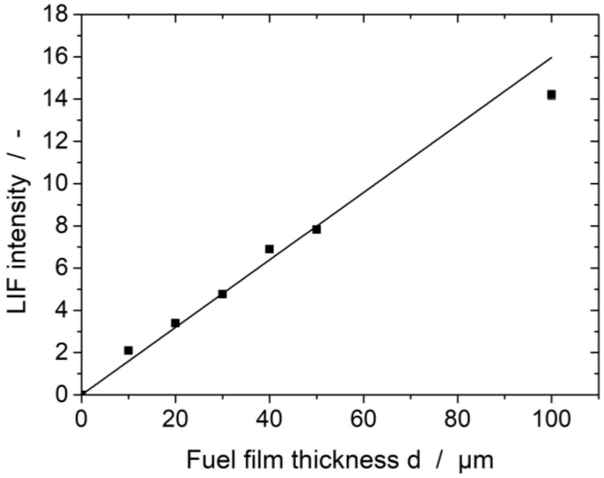
Fuel vapor

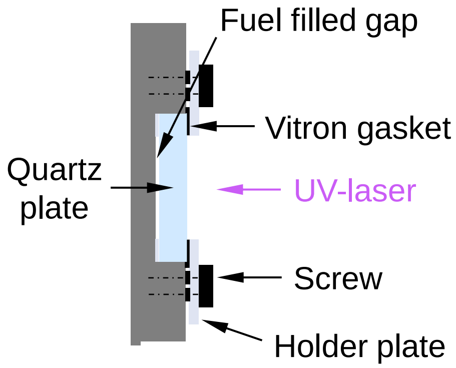
Fuel films

UV-laser

Injector

- Calibration tool enables in-situ calibration of LIF signal versus fuel-film thickness





Fuel filled gap

Vitron gasket

Quartz plate

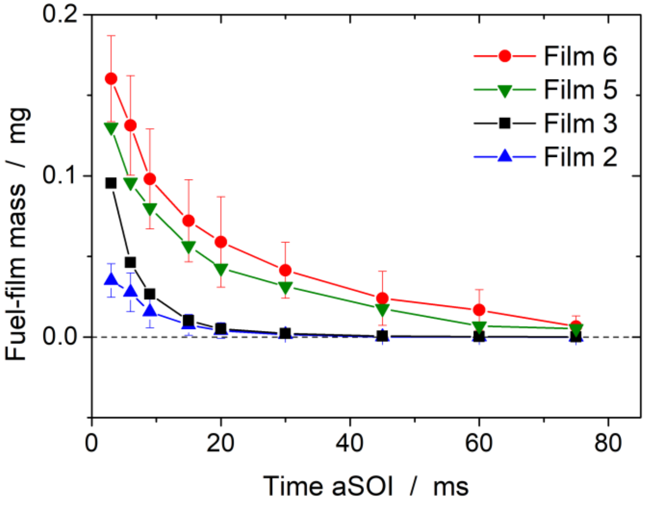
UV-laser

Screw

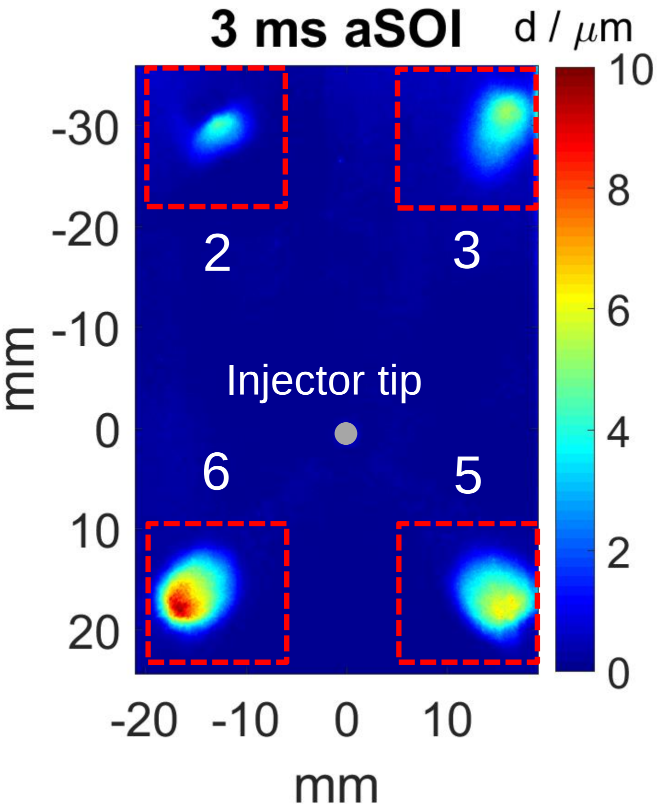
Holder plate

Fuel-film evaporation

- Fuel accumulates in the outer part of the wetted area
- Films 2 and 3 on average thinner than 5 and 6 due to longer impingement distance[1]



aSOI: after start of injection



- High evaporation rates in the beginning
  - Strong turbulence
  - Evaporation of thin parts => rapid decrease in film area

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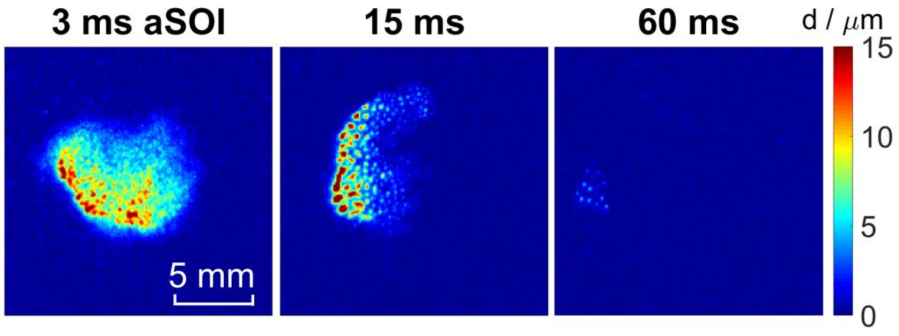
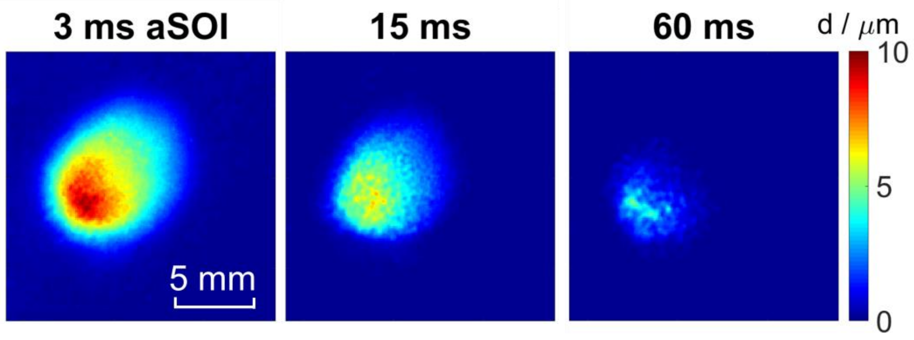
[1] Senda, J., Ohnishi, M., Takahashi, T., Fujimoto, H., Utsunomiya, A., and Wakatabe, M., SAE Technical Paper 1999-01-0798, 1999.

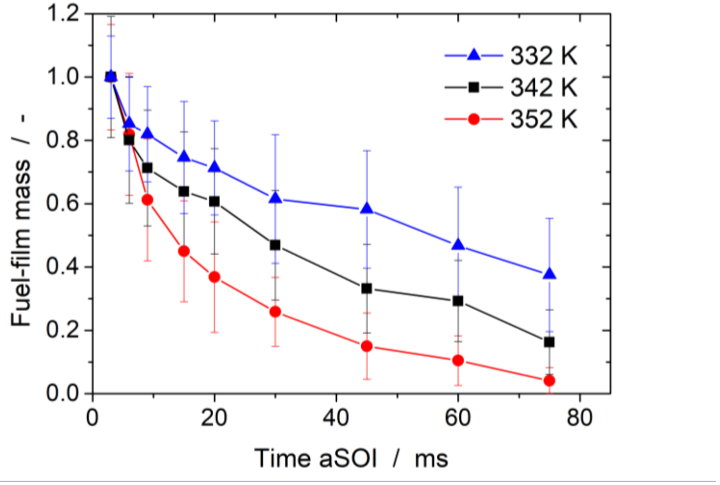
Fuel-film evaporation

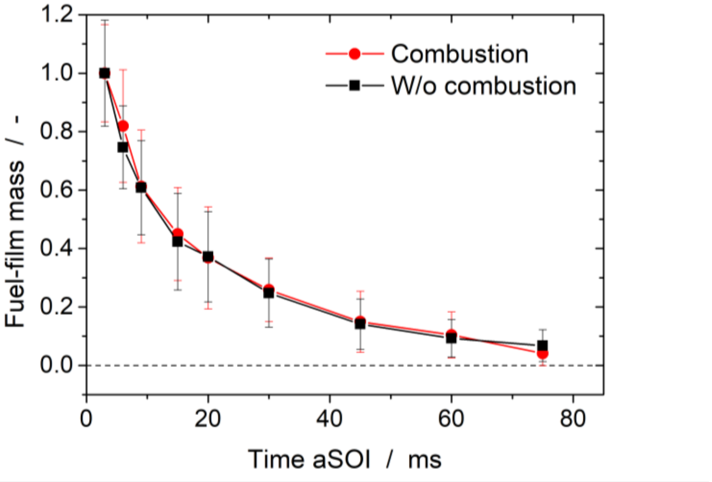
- Single shots and ensemble averages of the evaporating fuel film 6





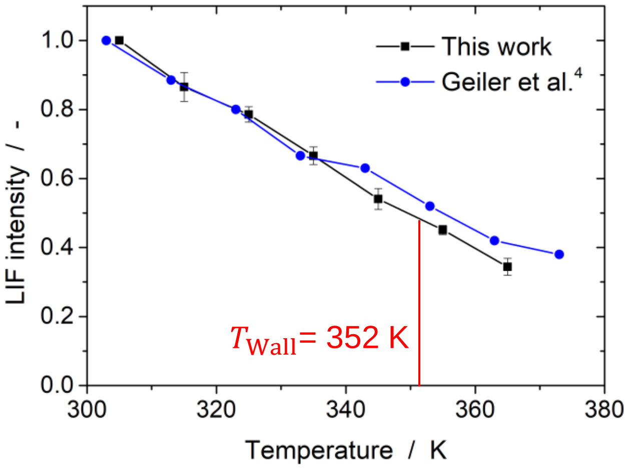
- Influence of wall temperature and combustion on evaporation





Calculation of fuel-film temperature

- **Motivation:** Temperature dependence of LIF signal of liquid toluene



- Assumption: Fuel film initially at injector temperature (361 K) and then approaches wall temperature

- **Objective:** Calculate the fuel-film temperature zero-dimensionally based on the measured evaporation rates and wall and air temperatures from a case without combustion

- **Outcome**
  - Fuel-film temperature
  - Wall temperature
  - Energy flows around fuel film
  - Plausibility of insights from experiments

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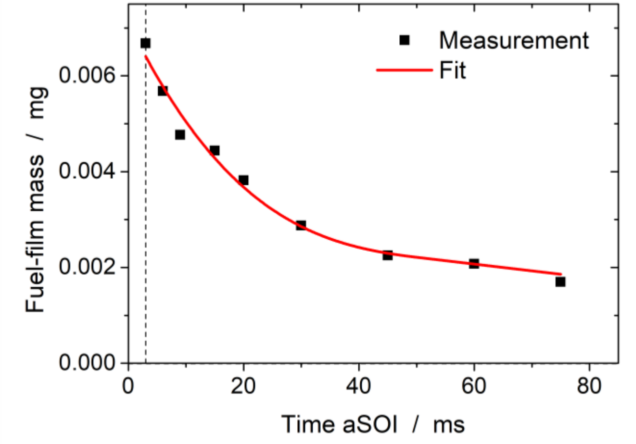
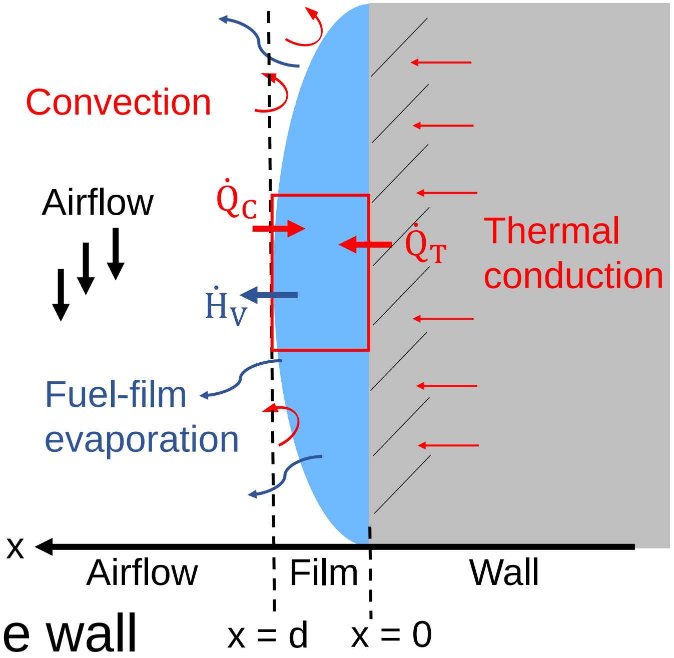
[4] Geiler, J.N., Grzeszik, R., Quaing, S., Manz, A., and Kaiser, S.A., "Development of laser-induced fluorescence to quantify in-cylinder fuel wall films," *International Journal of Engine Research* 19(33):134-147, 2018.

Energy balance around fuel film

- $$\underbrace{\frac{\partial T_{Film}}{\partial t}\cdot m_{Film}(t)\cdot c_V}_{\frac{\partial U}{\partial t}} = \underbrace{-\lambda_{wall}\cdot \left.\frac{\partial T}{\partial x}\right|_{x=0}}_{\dot{Q}_W} \underbrace{+\,\alpha\cdot A_{Film}\cdot (T_{Air}-T_{Film})}_{\dot{Q}_K} \underbrace{-\,\dot{m}_{Film}(t)\cdot \Delta h_V(t)}_{\dot{H}_V}$$
- $m_{Film}(t), A_{Film}$ and α from measurement:

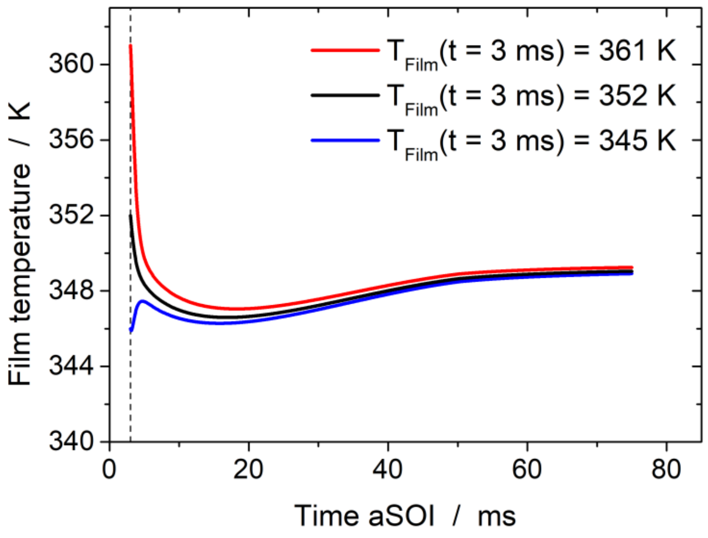


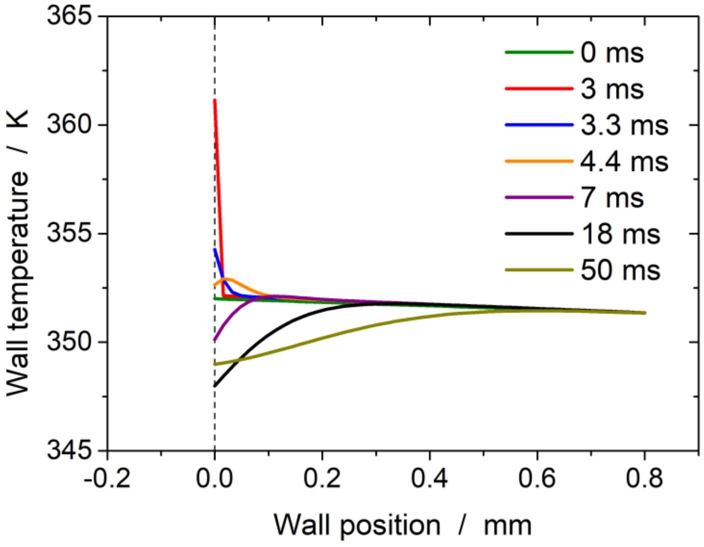


- $\left.\frac{\partial T}{\partial x}\right|_{x=0}$ from non-stationary heat transfer in the wall
  - $\frac{\partial T_{wall}}{\partial t} = a\cdot\frac{\partial^2 T_{wall}}{\partial x^2}$ => discretized according to Crank-Nicholson method

Fuel-film and wall temperature

- Initial fuel-film temperature unknown: Assumption of three different start temperatures
- Intitial quartz-wall temperature is 352 K
- Fuel film approaches initial quartz-wall temperature
- Wall temperature traces for initial film temperature of 361 K
- Thermal penetration depth of the wall is about 0.8 mm (10% of total thickness)

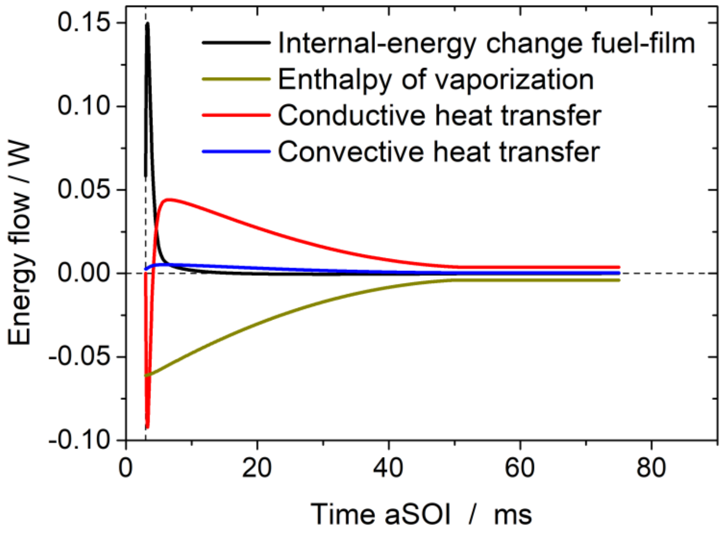


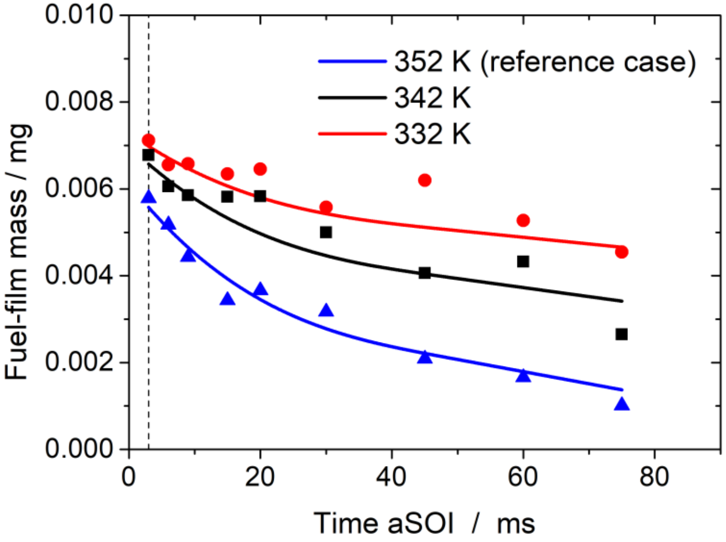


Energy flows and calculated evaporation

- Conductive heat transfer from the wall compensates for the evaporative cooling of the fuel film
- Convective heat trasfer has only a very slight influence

- Solving additionally mass transfer ($\dot{m} = \beta \cdot A \cdot (\rho_{sat} - \rho_{\infty})$) with mass and heat transfer coefficients from the reference case for varying wall temperatures





Conclusions

Experiment

- Imaging of fuel-film thickness and evaporation with tracer laser-induced fluorescence under different conditions
  - High evaporation rates early after the end of injection => high turbulence
  - Fuel accumulates to thick droplets (fuel „blobs“) during evaporation
  - Combustion has no influence on evaporation rates => conductive heat transfer from the wall is the driving force in evaporation

Model

- Zero-dimensional modelling of the film temperature based on experimental results and non-stationary heat transfer in the wall
  - Evaporative cooling of the fuel film is compensated by thermal conduction from the wall => convective heat transfer has very slight influence
  - Fuel film approaches initial wall temperature