PROCEEDINGS 8th ETH-Conference on Combustion Generated Nanoparticles
16-18 August 2004

In-cylinder soot concentration and soot temperature measurements

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Future demanding engine regulations require the optimization of the complete engine system: combustion and exhaust after treatment. For lowering the final particulate emissions it is important to reduce the particulate load originating from the combustion chamber and if required to apply after treatment measures. It is helpful, if not necessary, to understand the soot formation and soot oxidation processes itself.
To enable the engine researcher to handle this demanding task, a new tool is developed, which allows the temporal (crank angle) resolved measurement of soot concentration and flame (soot) temperature recorded within the combustion chamber. A versatile sensor with minimal invasive dimensions, robust and fouling resistant has been designed. The measuring technique is based on the well-known two color pyrometry principle.
By example of measurements on a heavy duty diesel engine as well as on a gasoline direct injected engine, the significance of such a measuring device is demonstrated in detail. The changes of soot development at different engine operating conditions can be investigated. For example we have found very good correlation between measured incylinder soot concentrations at the end of expansion stroke and particulate emissions in the exhaust gas. It is also possible to evaluate the soot temperature history, which plays a key role in the soot oxidation process. Moreover informations about the stability of the combustion process can be obtained with this method. Comparisons of several parameters of the heat release analysis and obtained measuring values show very good correlation.

Soot sensor

The soot sensor (figure 4) consists of an optical head with 3mm in diameter. It is small enough to place it e.g. into the glow plug of an Diesel engine. The optical head is connected by a light wave guide with an opto-electronic device. Inside the electronic box the signal is trifurcated and send through three different interference filters on three diodes.
The two color pyrometry is an optical measuring technique which is minimal invasive. Due to the small size of the sensor, it is easily integratable in a wide range of engines also with 4 valves. The optical head is kept clean, so fouling is not an issue. A wide bandwidth of sensitivity allows the application in heavily sooting Diesel engines as well a in direct injected gasoline engines.

Test measurements

In order two demonstrate the versatility of the sensor, test measurements have been carried out. Figure 5 describes the two engines used. In figure 6 the mounting position in the DI Diesel engine is schematically presented, as well as the position from the bottom view to the cylinder head. The sensor was directly placed with its field of view on the spray.

Results

The two color pyrometry delivers a KL-factor which is a measure for the soot concentration and the temperature of the glowing soot. Figure 7 shows the evaluated average signal of 72 cycles. The fuel burn rate is plotted over the crank angle. After fuel injection the first part of the combustion is premixed, because of a the ignition delay. Then more and more diffusion like combustion takes over. The soot formation (KL-factor) begins with the onset of the diffusion combustion. After 385°CA the soot gets oxydised. The soot temperature is plotted in figure 8. It lies between the calculated adiabtic temperature and the burned gas temperature calculated for an air/fuel ration of λ=1. In figures 9 and 10 a cycle-by-cycle evaluation has been performed. The soot development shows small variations from one cycle to the other, whereas the temperature stays relatively constant.

Measurements with different fuels have shown different sooting behaviour during the combustion cycle. If one takes the soot concentration after the strong oxidation phase and compares it with the opacity, a square correlation can be found (figure 11).

The sensor has also been applied at a gasoline direct injected engine. The change in sooting behaviour can be clearly observed (figure 12).

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8th ETH Conference on Combustion generated Nanoparticles
August, 17th, 2004
ETH Zürich, Switzerland

Motivation

- **Engine-sided measures decrease soot emissions**
  A good combustion management improves the emission performance and supports todays very effective after treatment technologies

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- **Understanding basic processes**
  It is helpful, if not necessary, to understand the soot formation and oxidation processes even in harsh environments

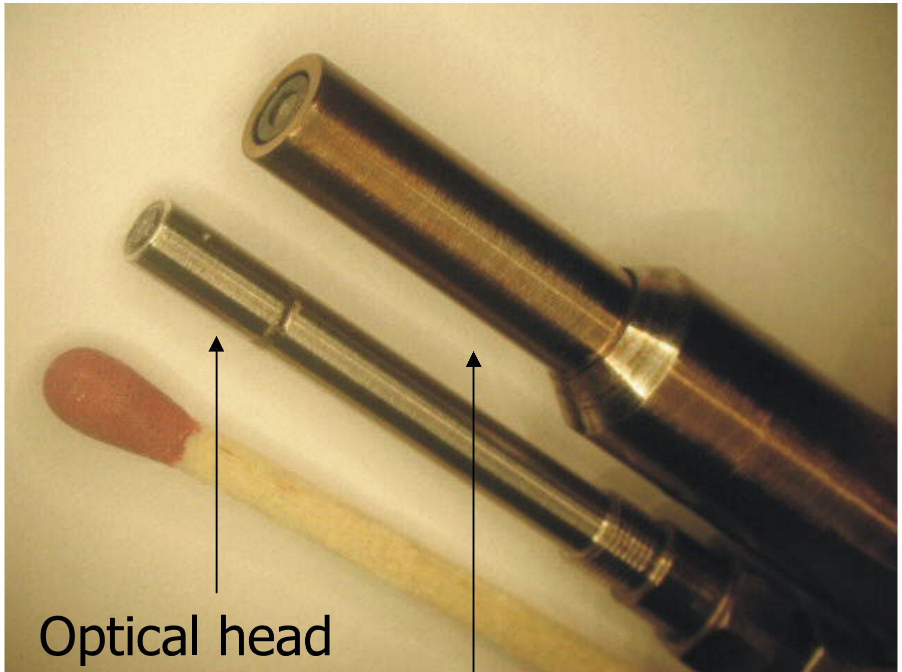
- **Tool for the application engineer**
  Observation technology for intuitive understanding of the influence of engine-sided measures like fuel composition, injection strategies, EGR variations on the soot development

Demands on a in-cylinder soot sensor

- minimal invasive, „non-intrusive" → **optical**
- integratable → **small-sized**
- mechanically robust
  thermally resistant → **construction**
- minimal degree of fouling
- wide bandwidth of sensitivity
  - DI Diesel -> Gasoline
    diffusion type -> premixed combustion
- handling, easy-to-use

The soot sensor

Optical Head



Glow plug

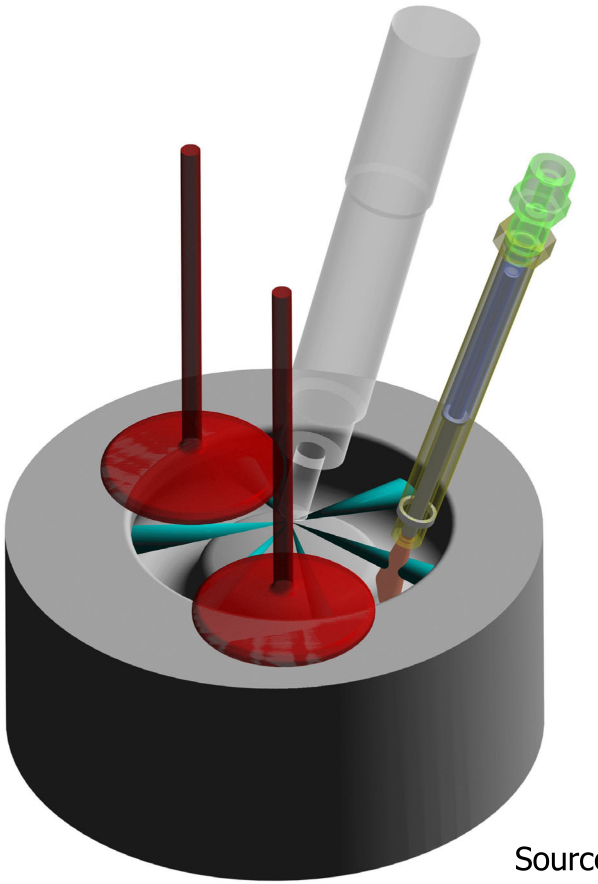
System

Two test engines

Application	**heavy duty**	**passenger car/ research engine**
Engine type	4-stroke Diesel 4 cylinder supercharged + charge air cooler	4-stroke gasoline (GDI) 1 cylinder supercharged + charge air cooler
Engine data		
B/H	122/142 mm	89.9/86.6 mm
V_h	6.6 l	0.55 l
P_e	183 kW	10 kW
n_{rated}	2100 min^{-1}	2000 min^{-1}
P_{memax}	20 bar	12 bar
Injection	direct fuel injection Common Rail	intake manifold fuel injection direct fuel injection *homogeneous charged* *stratified*

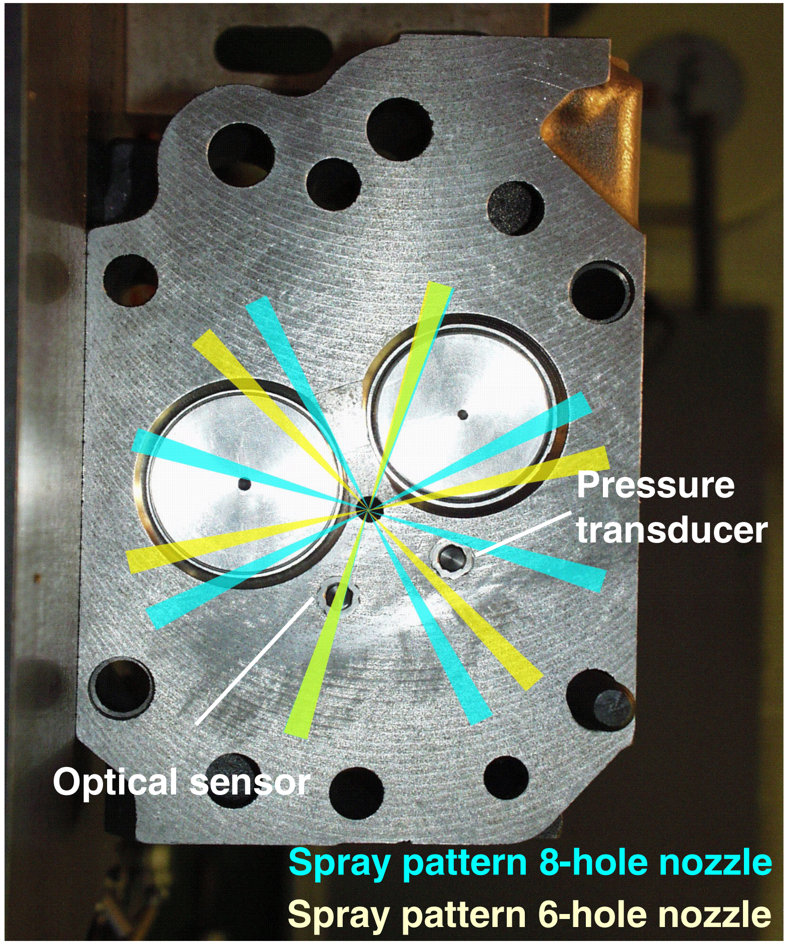
Sensor mounting position at the DI-Diesel engine

schematically

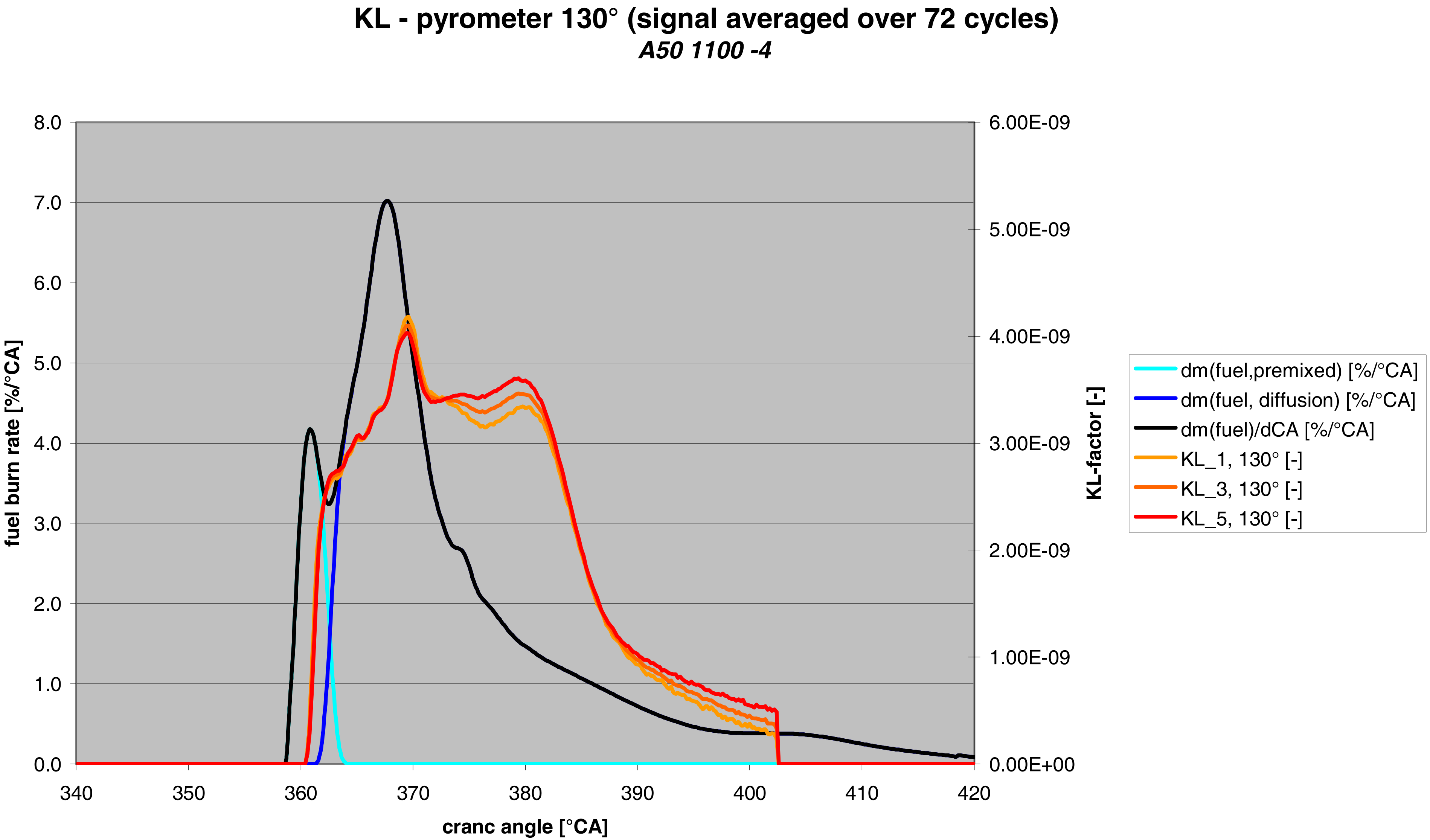


Source: Schubiger 2001

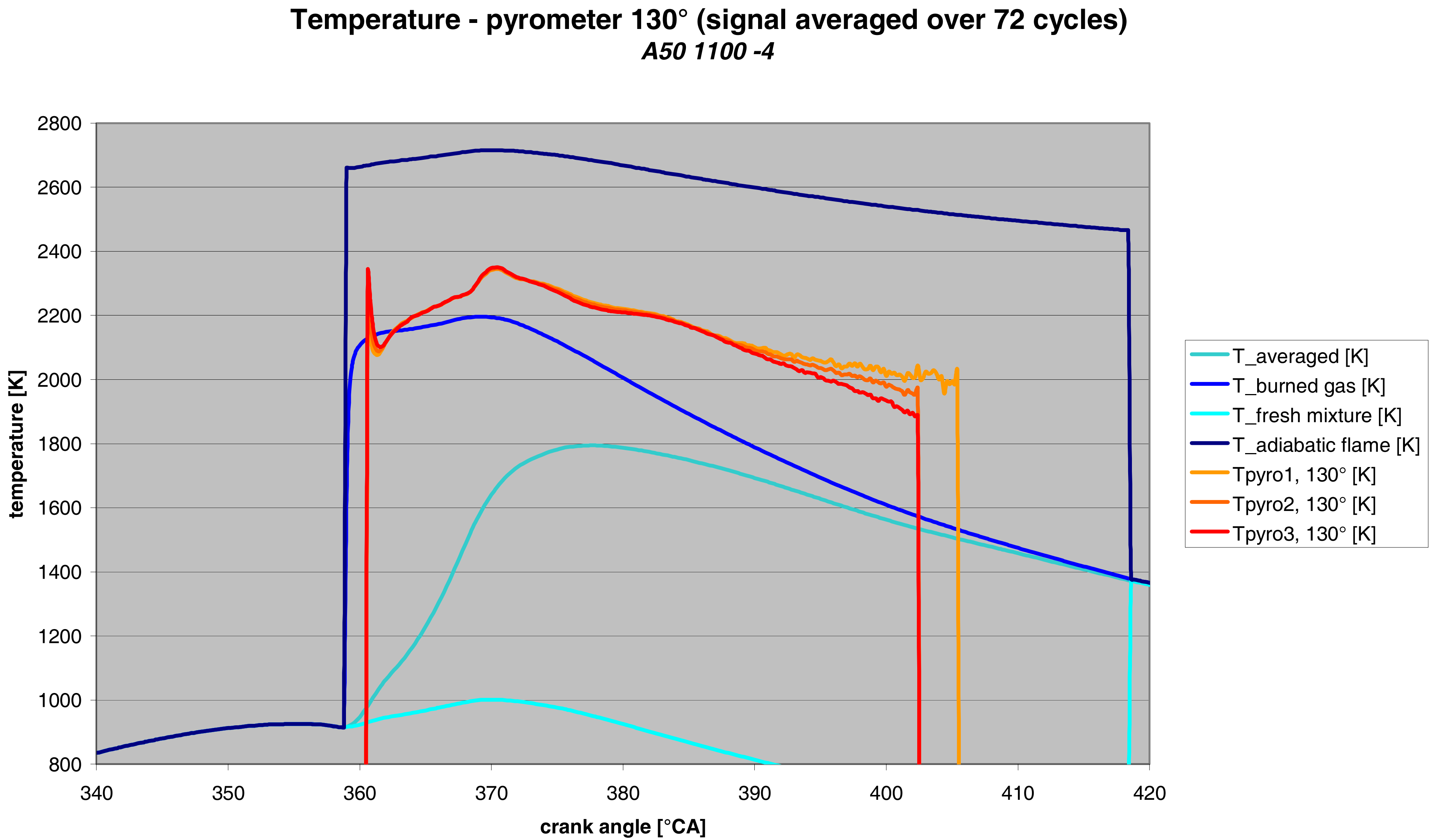
Position in cylinder head



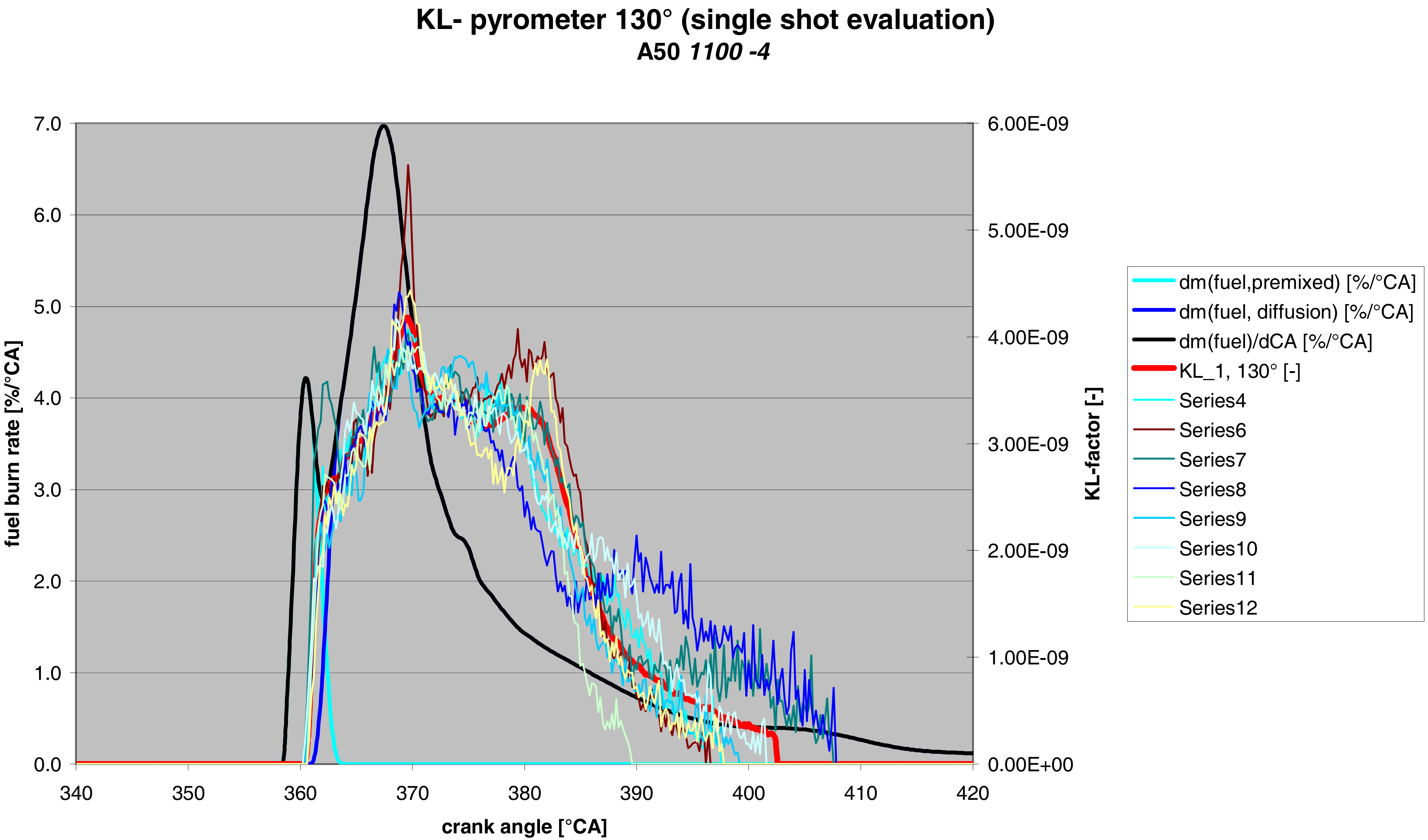
Soot concentration DI Diesel (avg)



Soot temperature DI Diesel (avg)



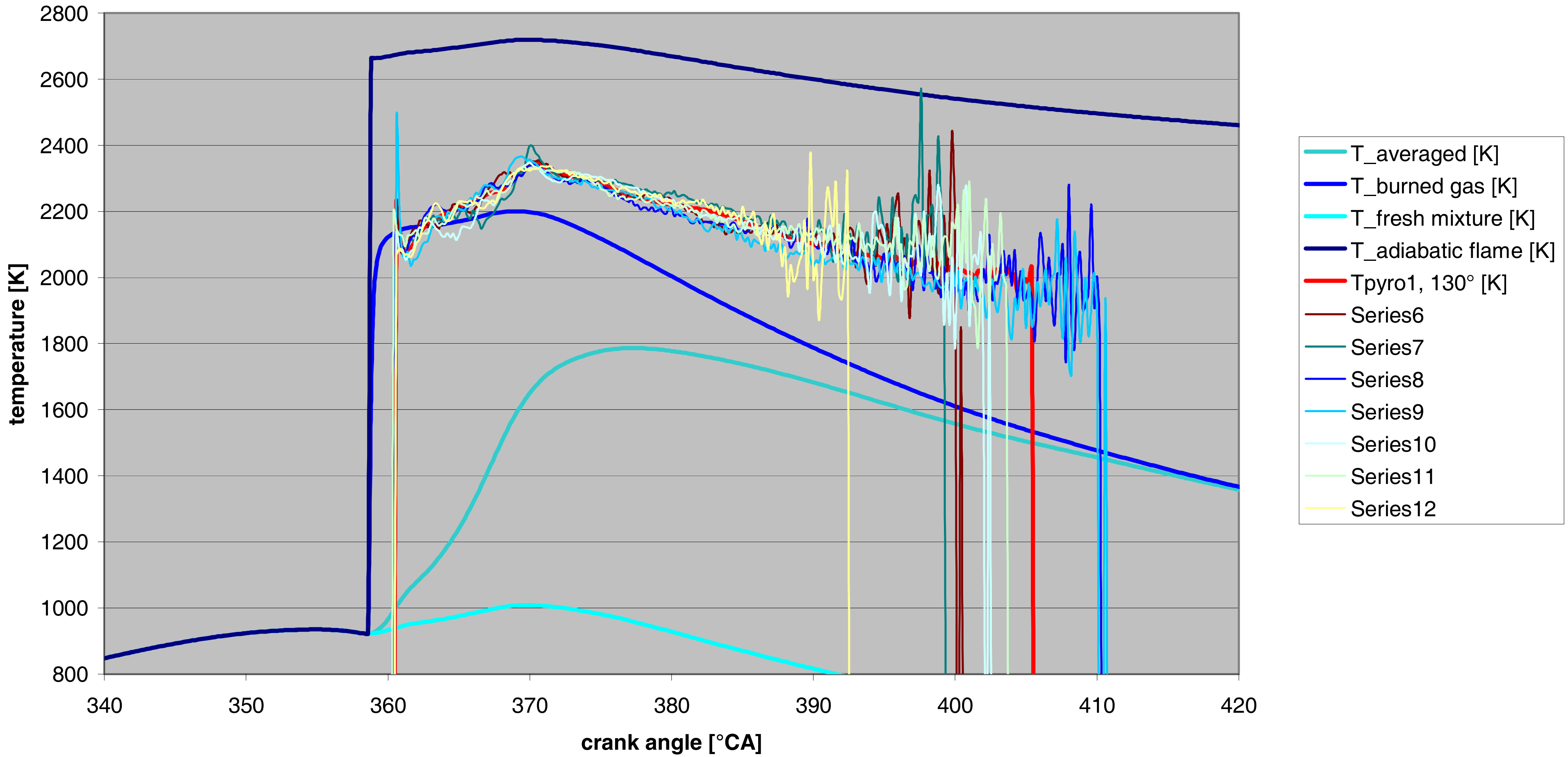
Soot concentration DI Diesel (single shot)



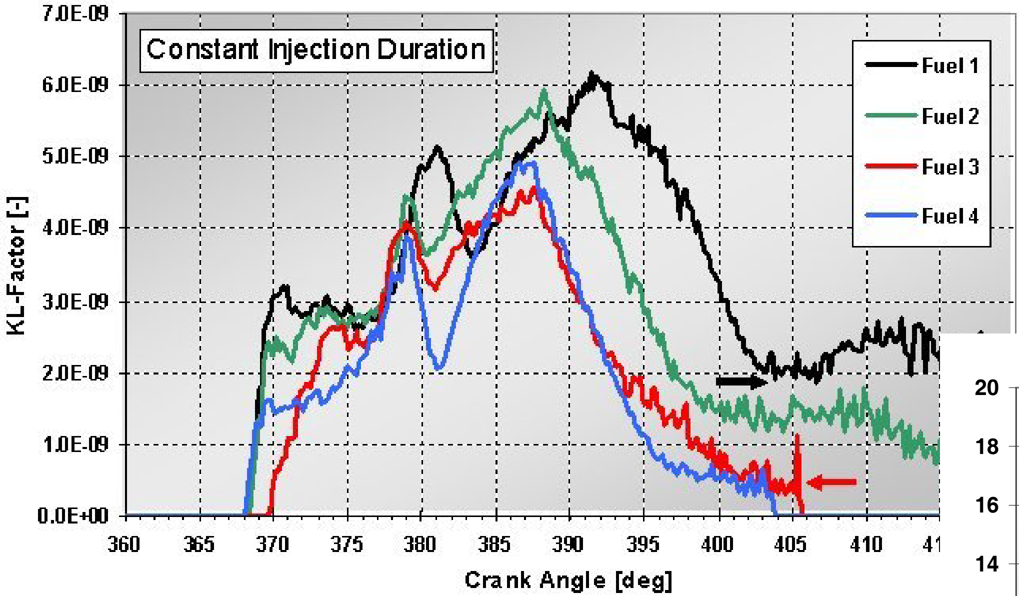
Soot temperature DI Diesel (single shot)

temperature - pyrometer 130° (single shot evaluation)

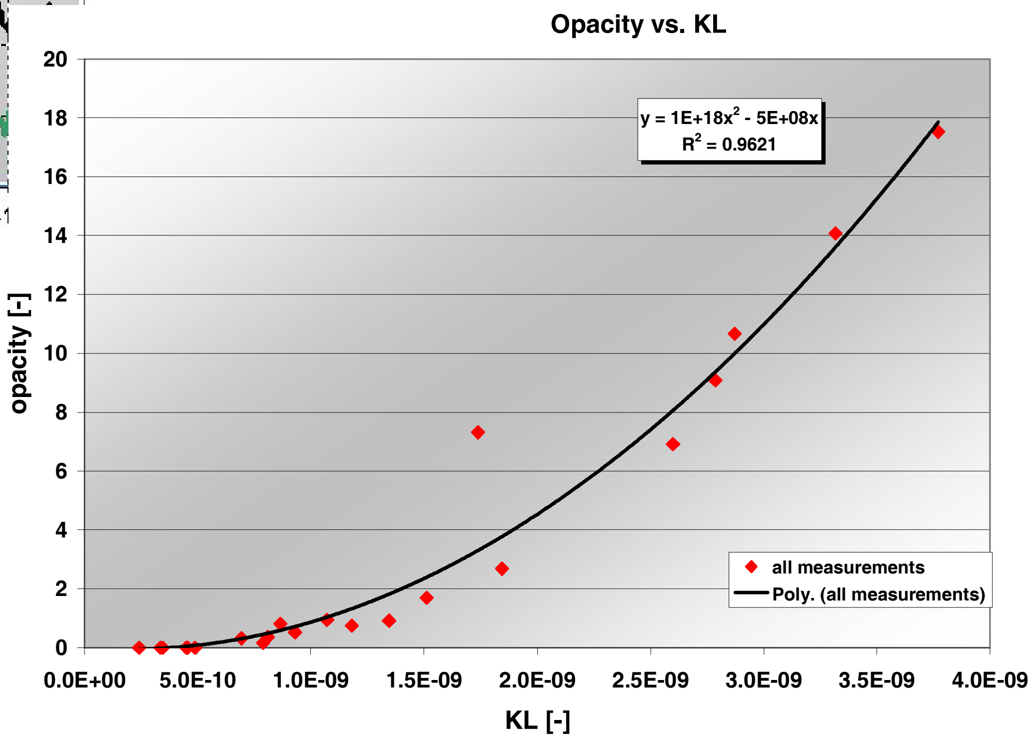
A50 1100 -4



Correlation opacity <-> KL-factor



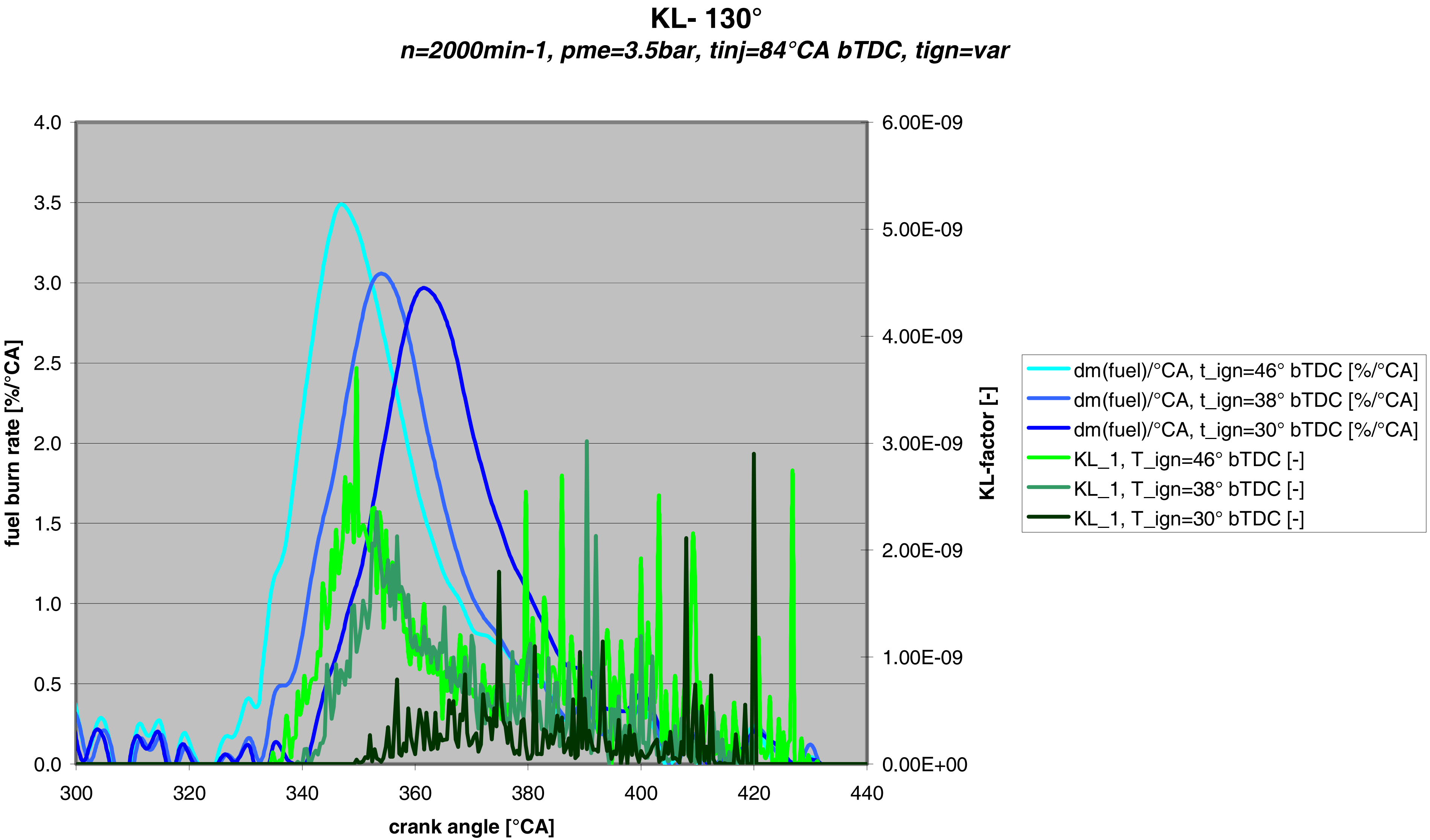
Opacity and KL-factor for all fuels and all operating conditions *)



KL development for 4 different fuels with constant injection duration *)

***) Here performed with the LAV sensor**

Comparison of soot concentrations: DI gasoline (avg)



Summary

- Soot concentration (KL) and soot temperature can be measured crank angle resolved
- The sensor can be used in Diesel engines as well as in DI gasoline engines
- Self cleaning is good enough: fouling is not an issue
- A correlation between opacity and measured KL could be found
- Sensor is small enough for passenger car engines

Acknowledgements

Institutions

- KTI Schweiz/CTI Switzerland

Companies

- Kistler Instruments, Switzerland
- LIEBHERR, Switzerland