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Abnormal combustion phenomena with different fuels in a spark ignition engine with direct fuel injection

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ABSTRACT

Characterizing abnormal combustion behavior of different fuels is of significant importance to explore the highest fuel economy and to improve the power density of modern spark ignited (SI) engines. Many experimental and numerical investigations have been reported in the literature for conventional pump fuels, whereas scientific findings for biofuels and gasoline-biofuel blends are less available. In the present study, special focus is set on the correlation of experimental investigations and corresponding auto-ignition theories. Therefore, the auto-ignition characteristics of biofuels and gasoline–biofuel mixtures for two different abnormal combustion phenomena (hot spot surface-ignition and gas phase auto-ignition under typical engine knock conditions) are studied using a direct injection spark ignition (DI–SI) single cylinder research engine featuring variable charge motion and a compression ratio of 11. The obtained results for all tested fuels are benchmarked against investigations using conventional E0RON95 fuel and isooctane as reference fuels. Additionally, kinetic investigations are performed to confirm the experimental results combined with auto-ignition theories. It could be shown via engine experiments with a controlled hot surface that the hot spot surface-ignition tendency is influenced by the chemical heat release rate of the fuel and the charge cooling effect due to the stoichiometric air requirement related heat of vaporization. Due to the increased enthalpy of vaporization with the applied (engine) configuration all gasoline–biofuel mixtures improve the hot spot surface-ignition propensity compared to the reference fuel E0RON95 by 20–50 K. The gas phase auto-ignition propensity decreases substantially with increasing ethanol content, revealing a boost pressure increase of at least 40–60 % under conditions typically relevant for knocking combustion in the end gas. For the applied configuration and with direct fuel injection, the location of auto-ignition has the highest frequency near the spark plug for all investigated fuels. Often, the most critical point for auto-ignition is the center electrode or the gas space in its immediate proximity between the ceramic insulator and thread.

1. Introduction and research objectives

Current development of modern SI engines focuses on direct injection and downsizing in combination with turbocharging [1–8] and increased cylinder pressures in order to increase efficiency of the engine cycle and hence reduce CO_2 emissions. The partial or complete replacement of fossil fuels by fuels from bio sources may help to further reduce CO_2 emissions from fossil sources.

The high octane rating of biofuels enables an increase of the geometric compression ratio and therefore an efficiency improvement in the entire engine map. However, high compression ratios combined with enhanced downsizing and new fuels are accompanied by challenges due to irregular combustion phenomena, whose control has not been fully understood yet. Besides spark knock as one of the major concerns and limiting factors [9–12], additional abnormal combustion phenomena, e.g., mega-knock or super-knock, occur in highly boosted SI engines [13–16]. Those combustion anomalies differ significantly from the conventional combustion processes and might lead to a strong impairment of engine operation or even to severe engine failures.

1.1. Classification of abnormal combustion phenomena and theories

In the course of this research combustion anomalies induced by hot combustion chamber surfaces and gas phase auto-ignition under typical engine knock conditions are investigated with different fuels. These anomalies can be allocated to different temperature regions (cf. Fig. 1).

In this figure the ignition delay times for neat ethanol (E100) and conventional E0RON95 fuel are depicted. For neat ethanol

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Nomenclature

ATDC	after top dead center
BDC	bottom dead center
BMEP	brake mean effective pressure
BTDC	before top dead center
CA	crank angle
CFR	Cooperative Fuel Research (Committee)
CO_2	carbon dioxide
DBL	detonation border limit
DI	direct injection
DOE	diffractive optical element
DVPE	dry vapor pressure equivalent
E0RON95	conventional pump fuel without ethanol
E20	E0RON95 + 20 %(v/v) ethanol
E85	E0RON95 + 85 %(v/v) ethanol
E100	neat ethanol
EC	exhaust closing
EOI	end of injection
ETBE	ethyl tert-butyl ether
ETBE20	E0RON95 + 20 %(v/v) ETBE
HTC	heat transfer coefficient
H_u	lower heating value
IO	intake opening
I20	E0RON95 + 20 %(v/v) iso-butanol
IMEP	indicated mean effective pressure
λ	relative air/fuel ratio
LHV	lower heating value
L_{st}	stoichiometric air requirement
M20	E0RON95 + 20 %(v/v) methanol
MFB50	mass fraction burned 50 %
MON	motor octane number
n	engine speed
NTC	negative temperature coefficient
PFI	port fuel injection
RON	research octane number
r_c	compression ratio
SOI	start of injection
TDC	top dead center

significant longer ignition delay times in the low and medium temperature regime are observed. However, in the high temperature regime the ignition delay times are slightly shorter compared to E0RON95. This divergent tendency for both fuels is mainly caused by the fuel specific kinetic differences in the corresponding temperature regimes. Low temperature gas phase auto-ignition is induced by a critical thermodynamic state of the in-cylinder charge. Hot spot surface-ignition events occur at temperatures above 1000 K and the high temperature kinetics of the fuels are more decisive.

The reaction kinetic processes for gas phase auto-ignition events in the cylinder charge are comparable to those of knocking combustion. Extensive investigations of knocking combustion with conventional fuels have revealed a two stage auto-ignition process in the end gas region [18–23]. These combustion anomalies are mainly determined by the low temperature chemistry of the fuel, as long as no hot spots or the presence of components with high ignitability (e.g., oil droplets) dominate the ignition process. Potential triggers for gas phase auto-ignition are mixture induced inhomogeneities of the cylinder charge, which lead to local temperature differences and therefore to exothermic zones in the combustion chamber. Optical investigations [18] and numeric simulations [24] have shown that already a slight temperature increase, compared to the surrounding gas phase, might be sufficient to provoke auto-ignition kernels. The local mixture composition as well as the thermodynamic state variables pressure and temperature are additionally influenced by the residual gas content. Thus, also hot recirculated or trapped residual gas in the combustion chamber has a significant impact on the occurrence of gas phase auto-ignition events [14,25,26]. Both, the high temperature and the reactive radicals in the residual gas reduce the ignition delay time of the in-cylinder mixture and have an accelerating effect on the auto-ignition process. Those influences result from the complex kinetic behavior of fuels, which heavily depends upon temperature, pressure, relative air–fuel ratio and exhaust gas composition [27]. Differences in the knock resistance as well as in the gas phase auto-ignition behavior are mainly associated to the zone of the so called cold flames [28,29] in a temperature regime between 800 and 900 K.

Increased surface temperatures may lead to an uncontrolled, early start of combustion by surface induced ignition and,

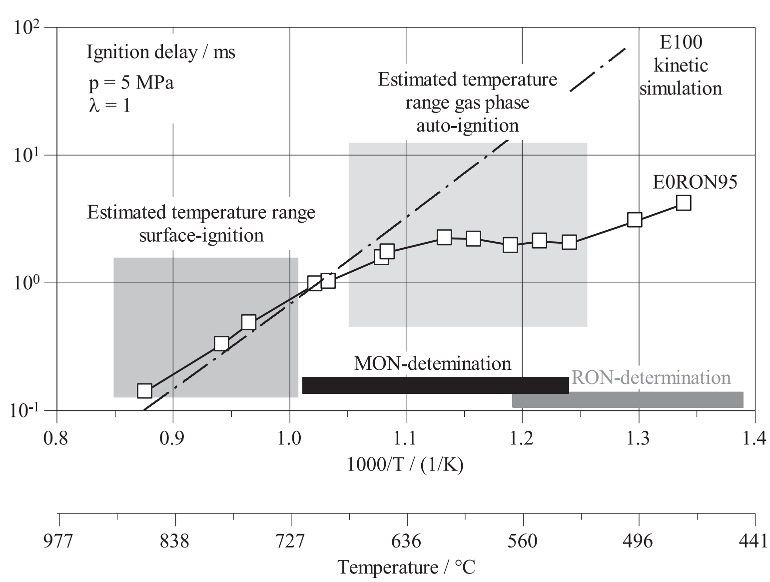

Fig. 1. Qualitative allocation of the investigated abnormal combustion phenomena as well as the temperature range of the octane rating determination in an ignition delay time diagram [17].

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