2011-01-1391

Glow-plug Ignition of Ethanol Fuels under Diesel Engine Relevant Thermodynamic Conditions

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ABSTRACT

The requirement of reducing worldwide CO_2 emissions and engine pollutants are demanding an increased use of bio-fuels. Ethanol with its established production technology can contribute to this goal. However, due to its resistive auto-ignition behavior the use of ethanol based fuels is limited to the spark ignited gasoline combustion process. For application to the compression ignited Diesel combustion process advanced ignition systems are required. In general, ethanol offers a significant potential to improve the soot emission behavior of the Diesel engine due to its oxygen content and its enhanced evaporation behavior.

In this contribution the ignition behavior of ethanol and mixtures with high ethanol content is investigated in combination with advanced ignition systems with ceramic glow-plugs under Diesel engine relevant thermodynamic conditions in a high pressure and temperature vessel. The investigation focuses on optimizing the injection conditions, especially injection pressure and rate. Optical measurements are performed by high speed imaging of the fuel injection and ignition, and evaluated in terms of ignition and flame propagation. The high speed imaging technology furthermore enables to gain information on the statistical behavior of the ignition process and thus provides a direct assessment of the repeatability of the ignition and combustion process.

The results of the ignition investigation aim at improving the understanding of the glow-plug induced ignition process in order to provide a reliable ignition strategy for the Diesel engine operation with fuel with high ethanol content. The results show that the favorable spray targeting relative to the glow-plug depends on the glow-plug design. Furthermore a moderate injection pressure improves the ignition reliability of the ethanol fuels. The latter leads to the hypothesis that reduced injection induced shear rates improve the ignition behavior by diminishing shear induced quenching in the ignition zone in the direct vicinity of the hot glow-plug surface.

INTRODUCTION

The increasing global energy demand conflicts with decreasing fossil energy sources. Thereby, a doubling of primary energy is assumed based on the rising economy of threshold countries like e.g. China, India, Russia and Brazil [1]. In order to enable prospective economical growth, alternative and regenerative energy sources and technologies need to be established in all sectors of energy engineering. Due to the limited power to weight ratio of battery systems, the application of hybrid technologies in combination with liquid biofuels appears to be one of the most promising sustainable and environmental friendly mobile propulsion developments.

In order to develop crude oil independent, carbon neutral biofuels, the cluster of excellence "Tailor Made Fuels from Biomass" has been initialized at RWTH Aachen University. Thereby, biomass waste products like e.g. wooden splints will used as a feed stock, avoiding the competition to third world food production. As one side project of this cluster, the application of ethanol to diesel engine applications is investigated.

THEORETICAL BACKGROUND

In the literature a large number of diesel related ethanol investigations can be found and only shortly described in this paper. Siebers et al. [2] investigated the limits of auto ignition stability in an insulated pressure vessel. It was found that auto-ignition of ethanol requires ambient temperatures of 900K. Since common passenger car Diesel engines in part load only achieve 800K at the end of compression, this limit of auto ignition stability demands additional measures. Saeed et al. [3] found out that an intake temperature of 450K was required for low part-load self ignition operation with ethanol and a compression ratio, which is not applicable in common passenger cars. The investigation of Hanson et al. [4] shows that the application of modern diesel engines can not compass the physiochemical borders of auto ignition behavior of gasoline related fuels. In order to ensure ethanol ignition in part load Karasawa et al. [5] investigated the ignition at a ceramic glow-plug in a motored two stroke engine by means of optical visualization, and identified different regimes of ignition.

Considering the spray model developed by Dec [6], a boundary layer with an ignitable air fuel ratio develops around the liquid spray core. At this position the hot glow-plug surface is located. The increased local temperatures in the vicinity of the glow-plug surface initiate the first reactions in terms of thermal decomposition of the fuel. The generated radicals initialize the combustion process downstream the glow-plug. With injector closing the flame separates from the glow-plug, burns out and extinguishes. Thereby, the glow-plug ignition process is coupled to simultaneous injection.

EXPERIMENTAL SETUP

TEST BENCH SETUP

The experimental investigations have been performed at the new high-pressure combustion chamber at the institute for combustion engines at Aachen University. The general test bench setup is shown in Figure 1. Two compressors provide a continuous air volume flow of $50m_n^3/h$ at 300bar. The air volume flow is dehumidified and buffered in a 480-liter storage vessel. By entering the laboratory the air volume flow is throttled to a maximum pressure of 150bar before entering the combustion chamber. Inside the chamber the air volume flow is electrically heated up to a maximum of 1000K. Along the line of sight within the measurement volume temperature gradients of approximately 1% peak chamber temperature can be achieved. Therefore, homogeneous and steady state conditions correlated to injection timing of common passenger car diesel engines in full load can be generated inside the measurement volume. The fuel is injected into this volume and the Diesel combustion related phenomena like evaporation, mixture formation, ignition and combustion behavior can be optically investigated through three windows which allow the application of various measurement techniques like e.g. shadowgraph visualization or Mie scatter light. Due to the continuous air volume flow, injection repetition rates of 0.1 Hz can be performed without exhaust enrichment inside the measurement volume. After leaving the combustion chamber, the exhaust gases are cooled down, filtered and throttled to 5-10 bar prior to air volume flow measurements and exhaust.

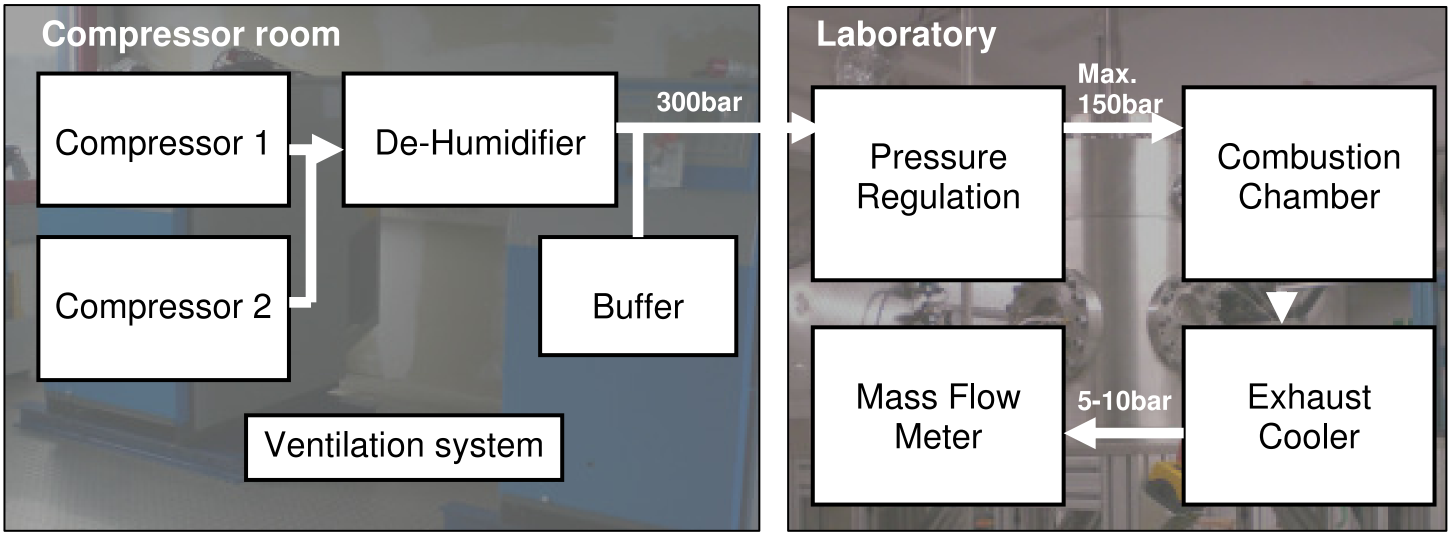

Figure 1 High-pressure chamber test bench setup

In order to investigate the glow-plug ignition behavior of ethanol fuels under diesel related conditions a glow-plug has been positioned in the vicinity of the injector nozzle. The adapted pressure chamber insert holding both injector and glow-plug, shown on the left side of Figure 2 has been designed.

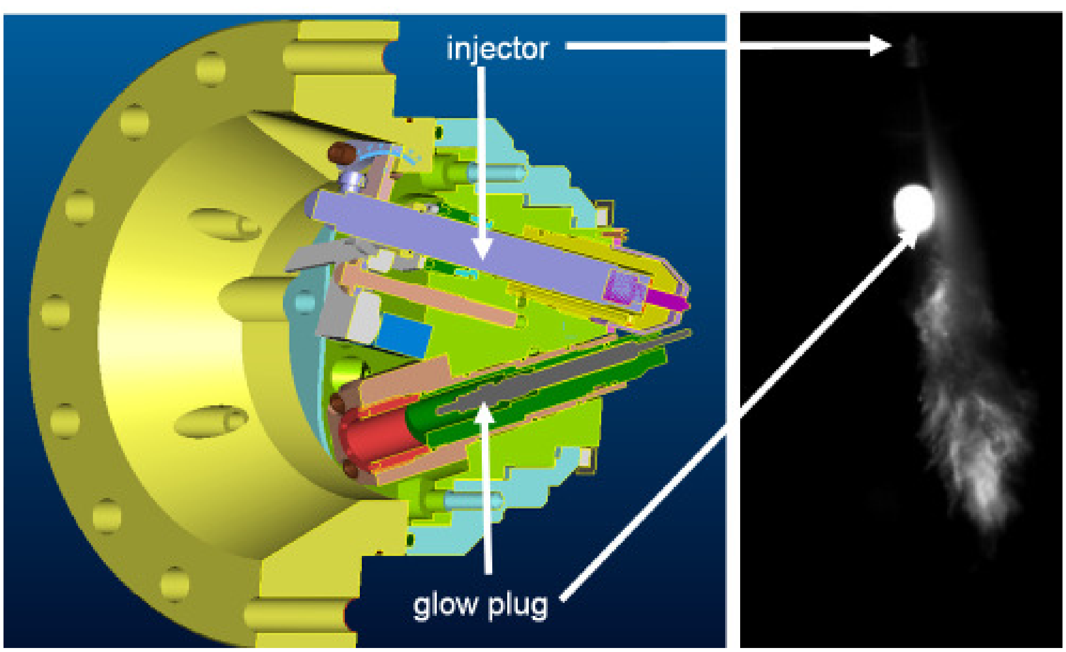

Figure 2 Customized Injector and Glow-plug holder and exemplary raw data flame radiation image in front view perspective

It can be seen that the injector is inclined towards the combustion chamber, directing the investigated spray cone vertically downwards towards the glow-plug. The injector is directly surrounded and cooled by water. An angle-scale fitted at the injector's spanner flat allows the precise repositioning after injector detachment. The glow-plug is positioned in an eccentrically hollow shaft allowing the modification of nozzle and glow-plug tip distance. The sealing towards the combustion chamber is done by a cone.

On the right side of Figure 2 an exemplary raw data image is shown. The nozzle tip is visible at the upper image border. The bright spot in the upper half of the image is the hot glow-plug surface of the uncovered, ceramic glow-plug. In order to avoid thermal shock by direct fuel impingement at the hot glow-plug surface, the injector is twisted by 10° around the injector axis in all these experiments. Downstream of the glow-plug broadband flame radiation can be seen

EXPERIMENTAL PARAMETERS AND STRATEGY

In Table 1 the investigated chamber conditions, hardware configurations and experimental variation parameters are given. The chamber pressure of 40bar correlates to in-cylinder conditions of a passenger car diesel engine at the end of compression in part load operation. In order to investigate the limits of glow-plug ignition, the chamber temperatures selected for this investigation are significantly below the common in-cylinder temperatures at this operation conditions, and can be related to diesel engine cold start operation.

Table 1 Experimental parameters

Chamber temperature	444 - 531 K
Chamber pressure	40 bar
Glow-plug type	Ceramic without cover
Injector twisting angle	10°
Rail pressure	400 - 1000 bar
Fuels	100% Ethanol 80vol% ethanol with 20vol% Dodecane
Injection strategy	Single Injection: tinj = 450µs, 1ms, 2ms Split Injection: tinj1 = 180µs tinj2 = 300µs Split injection: tinj1 = tinj2 = 225µs

The selection of the glow-plug type and injector twisting angle is based on preliminary experiments not presented explicitly in this paper. The ceramic glow-plug is chosen due to its superior ignition conditions in comparison to metal glow-plugs. A glow-plug cover is not applied here, since pre-investigations have shown, that the reduced fuel contact to the hot surface resulted in increased ignition delays. Due to the flame extinction with injector closing, the increased ignition delay caused increased probability of incomplete ignition or misfiring.

During the measurements, the glow-plug ignition of ethanol and ethanol blended with 20vol% dodecane is investigated at rail pressures from 400 to 1000bar. Additionally, three different injection strategies are investigated: single injections of 450, 1000 and 2000µs, split injections with 180µs pilot and 300µs main injections and split injections with symmetrical actuation duration of 225µs each. The sum of split injection actuation duration roughly correlates to the short single injection strategy. According to Figure 3 the time delay between first and second actuation is varied additionally for the pilot and the symmetrical distributed split injection strategy. In the following discussion a time distance between first and second actuation of 1000µs will be named S1, a time distance of 600µs will be named S4.

Due to the large matrix of variation parameters in combination with the required conditioning time in order to achieve steady-state chamber conditions, a restricted number 5 five injections per operation point are recorded.

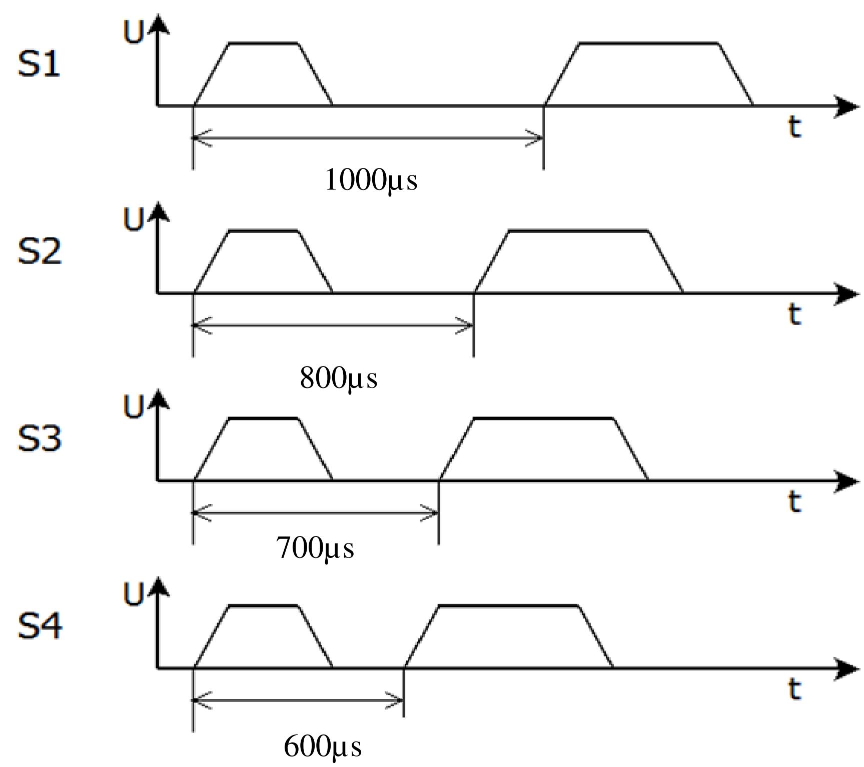

Figure 3 Split injection variations

DATA ACQUISITION

OPTICAL SETUP AND TRIGGERING

For the investigation of ignition boundary conditions and the cyclic stability of flame propagation, high-speed flame visualizations are performed. Therefore, a high-speed camera with a Nikon AF-D 105mm/2,8 lens was positioned at the window opposite to the injector and glow-plug holder. The camera operated with temporal and spatial resolution of 6000 frames/s and 256Pixel*512 Pixel. The CCD sensor can detect wavelengths between 400 and 1000nm with a peak quantum efficiency at 600nm. A raw data image of the broadband flame visualization is shown on the right side of Figure 2.

In order to avoid jitter in the triggering of the camera relative to the injection actuation, a self synchronizing triggering scheme shown in Figure 4 is used. A master TTL signal with a repetition rate of 0.1 Hz and a pulse width of 170µs is logically coupled in an AND gate with the camera sync out signal. Therefore, a camera synchronized triggering signal is given to the pulse delay generator each 10 seconds. The delay generator triggers the camera and the injector power stage. This assures that the injector operation is always synchronized with the internal camera clock and its recording. The triggering signal given to the power stage is modified for each variant of the (split-) injection strategy. The power stage is generating the injector actuation signal. The recorded images are sent to the measurement computer after stopping the image acquisition.

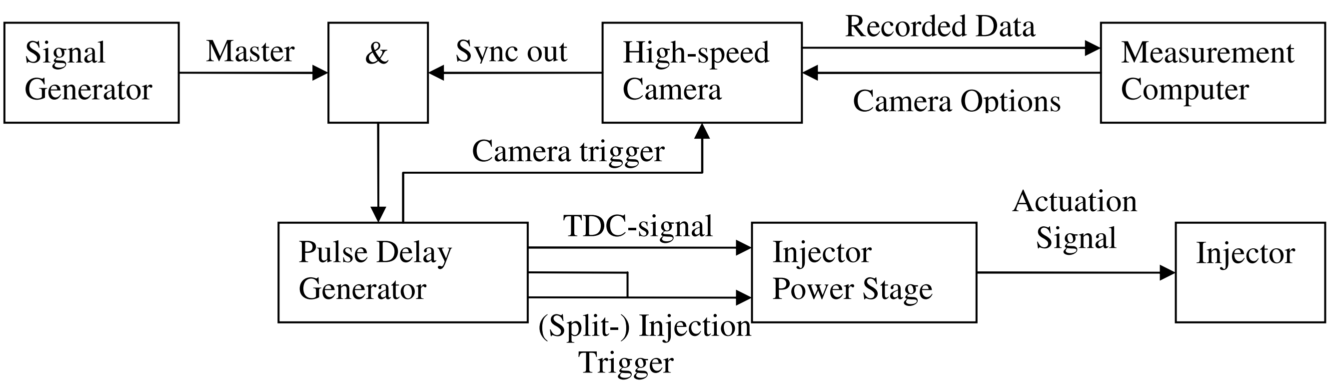

Figure 4 Triggering Scheme

POST-PROCESSING AND STATISTICAL EVALUATION

For the identification of flame radiation and statistical evaluation the raw data images need to be post-processed. On the right side of Figure 5 the background image including the radiation of the uncovered ceramic glow-plug, reflections at the injector nozzle and scatter light from liquid fuel droplets in the vicinity of the glow-plug are shown. As these effects do not contribute to flame radiation, the background image needs to be subtracted from all following images of this injection event. As a result, the frame subtracted image shown in the middle of Figure 5 contains only information arising from the broadband flame radiation. Subsequently the frame subtracted images are binarized with a suitable threshold. The binarized images at a given time increment are averaged over all cycles recorded to provide a spatial probability distribution of flame radiation at this time increment, as shown on the right side of Figure 5. The probability of flame radiation is coded here by colour fill of the flame contour. As shown in the color bar on the right, image areas with 100% probability of flame radiation are colored black, areas with 0% flame radiation probability are colored white. The position of the nozzle and glow-plug tip are marked with a x and a + symbol.

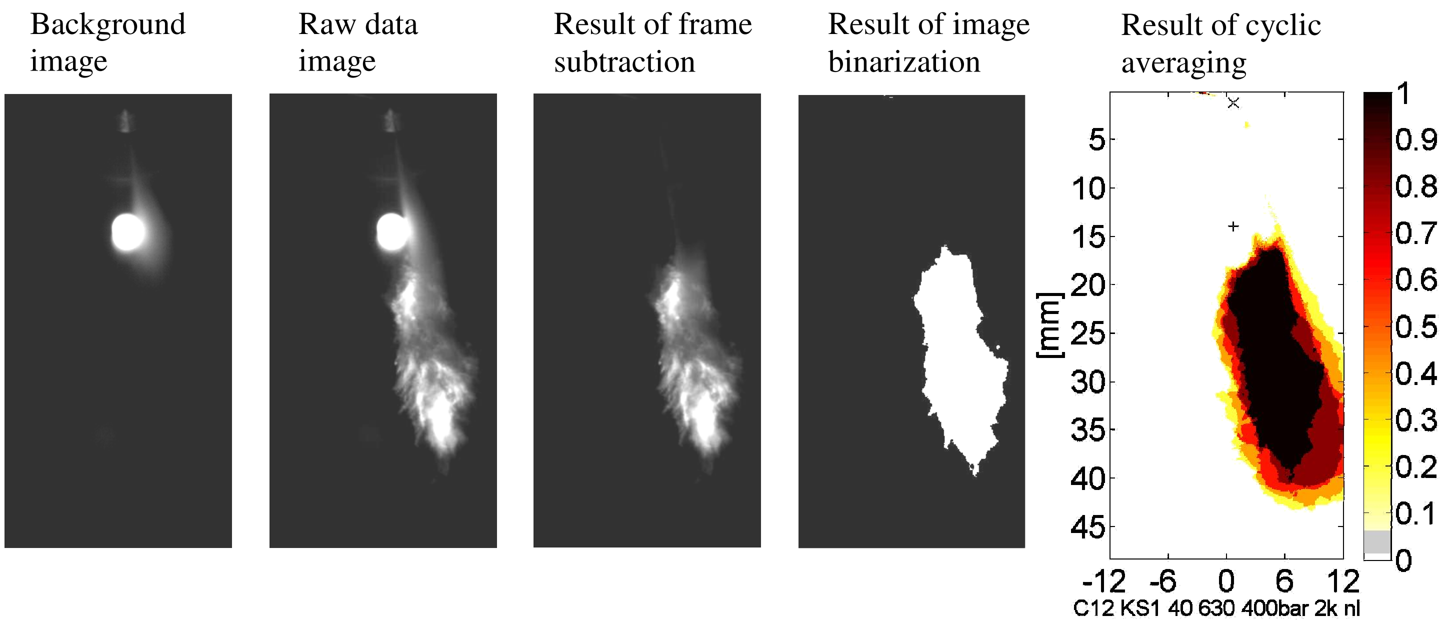

Figure 5 Raw data post-processing procedure

Based on the computation of spatial flame probability distributions shown in Figure 5, dimensionless ignition characteristics are calculated for the quantification and comparison of individual operation points. Major focus of these investigations is the quantification of glow-plug ignition probability and stability. Therefore, the following two characteristic parameters are defined.

Relative number of misfire (RNM)
For the detection of misfiring cycles the size of the projected flame radiation surface in the binarized images are used. In order to avoid falsifications only cycles with flame radiation surface larger than $30mm^2$ are detected as sufficient ignition. The number of misfires is normalized by the total number of injections.
Therefore, a high RNM value is indicating insufficient ignition stability

Relative Reproducibility of projected flame surface (RRPFS)
In order to quantify the cyclic stability of flame propagation the area with 100% flame radiation probability is normalized to the area with more than 0% flame radiation probability. In terms of image analysis, the black area of spatial flame radiation probability distribution is divided by the complete colored and black area of this distribution. In order to account for the temporal behavior of the flame propagation, an adequate time averaging procedure has been developed, which is shown in Figure 6. Here it can be seen that the cyclic reproducibility of the flame propagation improves from ignition to a quasi steady state before it degrades towards flame extinction. In order to provide one dimensionless parameter representing the complete quasi steady state period, all relative flame surfaces that are less than 0.31 units below the maximum are averaged to the RRPFS parameter.
Therefore, a high RRPFS number is indicating a good cyclic stability of flame propagation in the quasi steady state period. On the other hand, a RRPFS value of zero directly indicates one or more misfiring cycles as misfiring cycles result in no area with 100% probability of flame radiation within the images of flame radiation probability distribution. Therefore, both RRFS and RNM parameters are complementary.

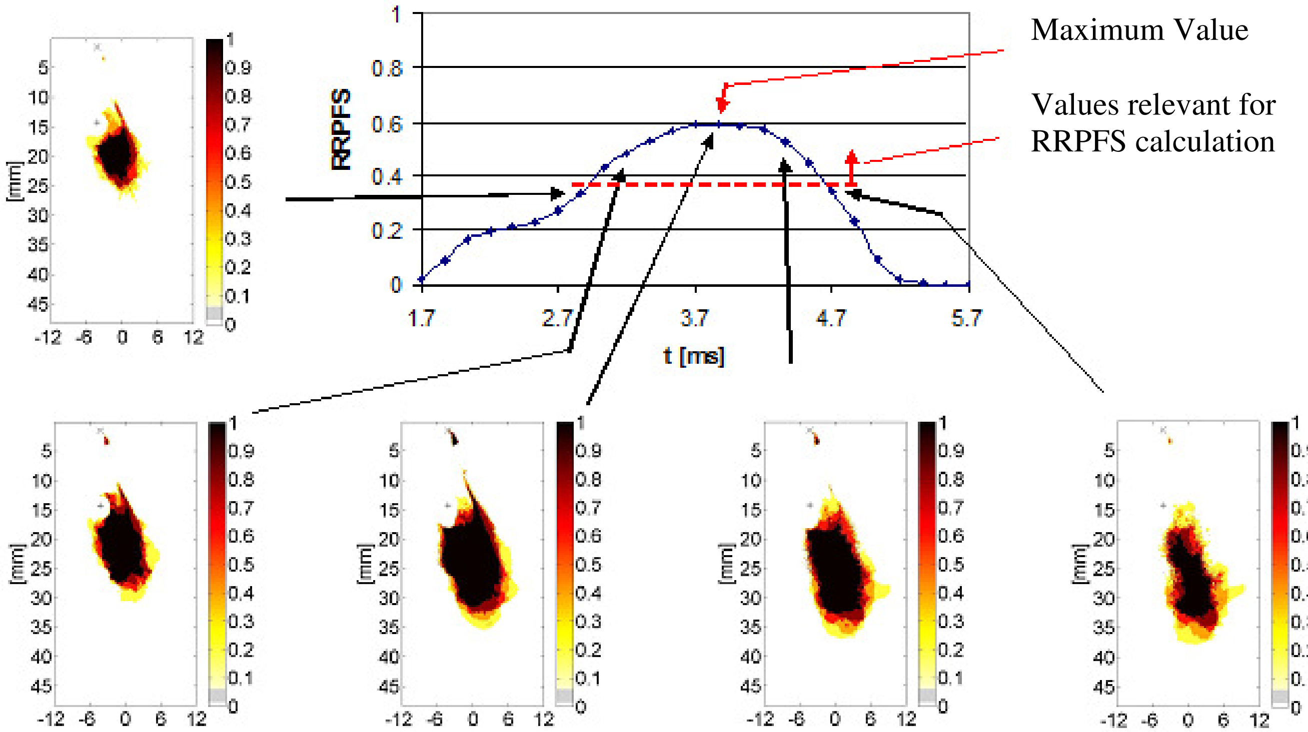

Figure 6: Procedure for the calculation of the relative reproducibility of projected flame surface

EXPERIMENTAL RESULTS

EXEMPLARY RESULTS

In Figure 7 the effect of rail pressure is exemplary shown for experiments with ethanol at 478K and 450µs single injection actuation. In the upper row raw data images of the flame radiation light during the first injection event with rail pressures from 800 to 400bar are shown. In this example all first injection events ignite and the flame shape is comparable for the three injection pressures. In the lower row the probability distributions of these measurements are shown. Thereby, it can be seen that the stability of ignition and reproducibility of flame propagation is significantly influenced by the rail pressure. With 800bar rail pressure a maximum probability of only 0.8 is detected. Due to the five cycle statistic this value represents one complete misfiring cycle. Moreover, the flame expansion underlies strong cyclic fluctuations. With 600bar rail pressure a minor area of 100% flame radiation probability in the vicinity of the glow-plug caused by one retarded and incomplete ignition can be seen. In contrast to this a large area of 100% flame probability is detected with 400bar rail pressure indicating a sufficient ignition stability and flame propagation reproducibility.

The beneficial effect of decreased rail pressure on the stability of glow-plug ignition is assumed to be caused by decreased turbulent dissipation in the vicinity of the glow-plug. Thereby, initial combustion intermediates remain in the vicinity of the hot surface and enhance the ignition process. With increased rail pressure initial combustion reactions are extinguished by the deviation of those initial combustion intermediates.

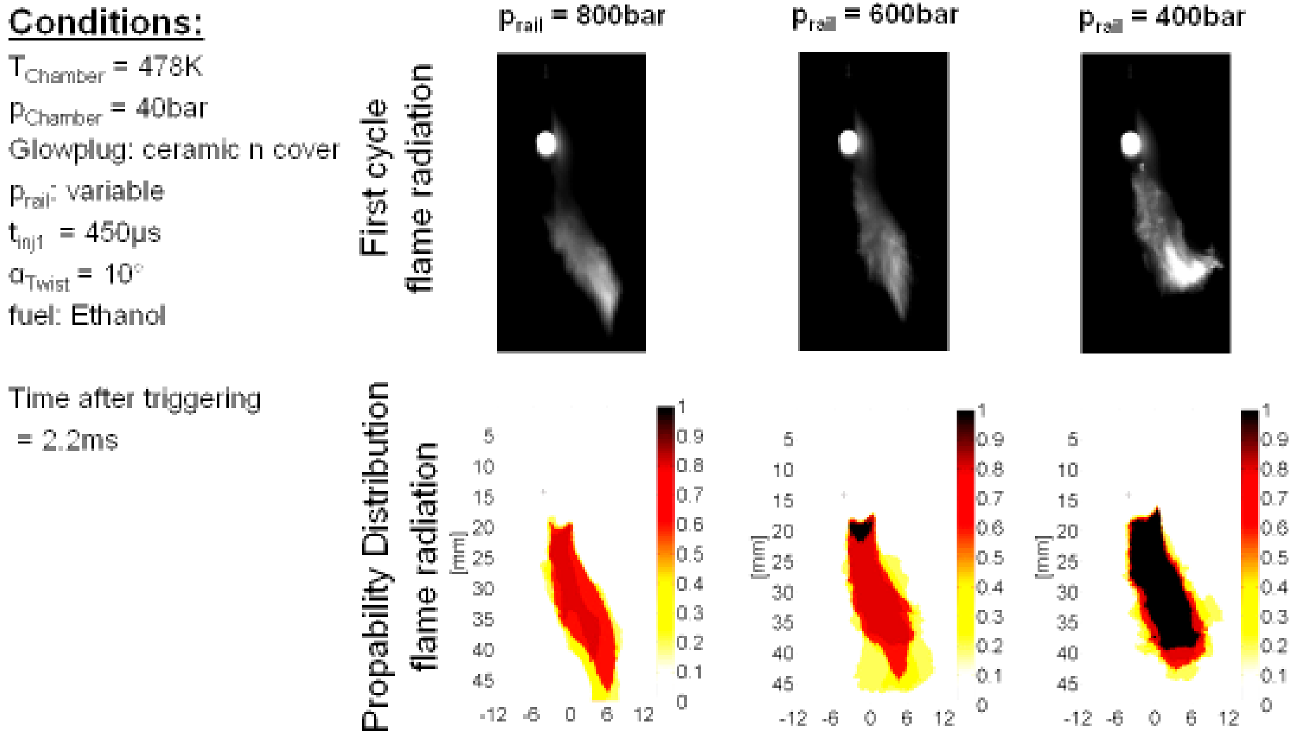

Figure 7 Effect of rail pressure on ignition behavior of ethanol

STATISTICAL EVALUATION

Investigation of 100% ethanol

In Figure 8 the RRPFS and RNM values of the experimental high-speed flame visualization experiments with 100% ethanol at rail pressures from 1000 to 400bar are shown. On the x-axis the investigated injection strategies are shown with C12 for single injections with 450, 1000 und 2000µs actuation duration, C13 for split injections with pilot and main actuation and C14 with equally distributed split injections. The delays between these split injections vary from 1000, 800, 700 und 600 µs according to S1 to S4 as shown in Figure 3. On the y-axis the chamber temperatures from 444 to 531 K and on z-axis the RNM and RRPFS values are given.

In the top row of Figure 8 the RNM and RRPFS values for the experiments with 1000bar rail pressure are given. Based on the RNM values, it can be seen that misfiring cycles are detected with all configurations and temperatures resulting in zero RRPFS values as no 100% probability of flame radiation is given. This directly indicates that this rail pressure is improper for engine glow-plug ignition applications with pure ethanol. According to single injection strategies C12, the relative number of misfires is generally reduced by increased actuation durations. This is due to the fact, that more fuel is injected and theoretical time period for ignition is increased. In comparison to 450µs single injection, the number of misfires is increased with all split injection strategies as the theoretical time for the individual sufficient ignition per injection is reduced. In general, a slight minimum of RNM values is given at 508K, which is surprising as higher temperatures should enhance reaction kinetics and thus improve ignition stability. This effect could be caused by temperature and gas density affected equivalence ratios in the vicinity of the glow-plug.

The RNM and RRPFS values of experiments with 800bar are given in the second row of Figure 8. Thereby, it can be seen that reproducible ignition can be achieved with individual configurations although statistical the data is superposed by noise based on the five cycle statistic.

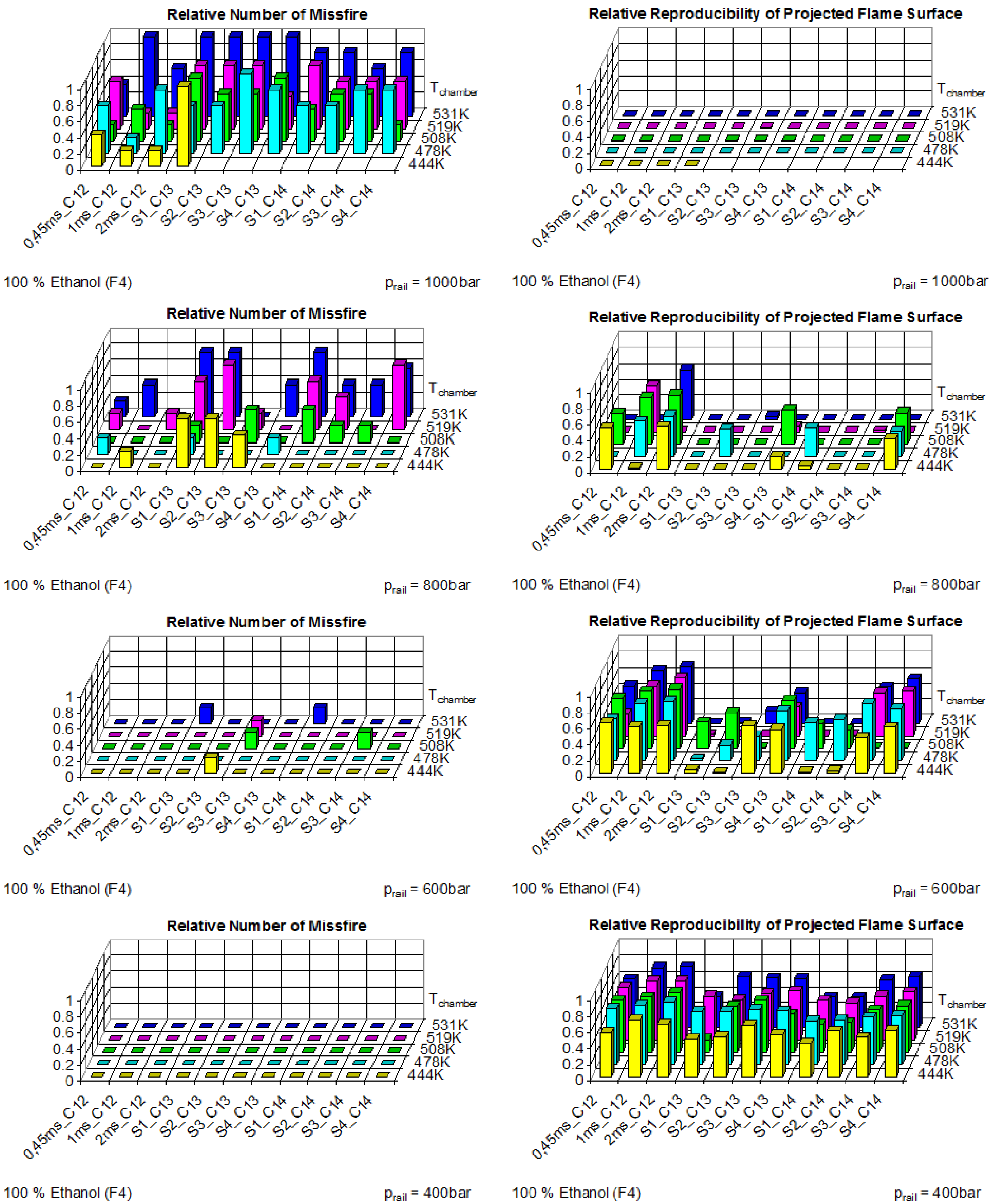

Figure 8 Statistical evaluations of ethanol glow-plug ignition stability for varying rail-pressures

According to the single injection strategy, the number of successive ignitions and the reproducibility of flame propagation benefit from actuation durations above 1ms. Thereby, no misfires are detected with 508K. With split injection strategies no definite trend can be observed at this rail pressure due to the statistical uncertainties.

At 600bar reproducible ignition with sufficient reproducibility of flame propagation is detected for all single injection experiments. Increased single injection actuation duration results in improved RRPFS values for all temperatures except 444K. The RNM values of split injection strategies do not exceed 0.2 representing one misfire during five injections. Based on the RRPFS values a beneficial effect of reduced time distance between the split injections can be seen. This result is based on the fact that complete closing of the 3-hole injector at 600bar is inhibited by time distances of less than 700µs between both actuations. Thereby, flame extinction by injector closing is avoided. Moreover, pressure throttling is caused by the partly closed injector needle resulting in decreased spray velocity and reduced turbulent dissipation. The optimum temperature seems to be 478 and 508K.

In the bottom row of Figure 8, the RNM and RRPFS values for measurements with 400bar are given. Thereby, it can be seen that no misfiring cycles are detected at all, indicating that decreasing rail pressure is one of the major parameters for sufficient glow-plug ignition stability and reproducibility of flame propagation. Moreover, the beneficial effects of increased actuation duration and decreased time distance between split injections are visible.

Investigation of 80vol% ethanol and 20vol% dodecane

The effect of ignition enhancing is investigated with a blend of ethanol and dodecane in low chamber temperature range of 444 to 478K. The resulting RNM and RRPFS values of these experiments with rail pressures from 1000 to 400bar are given in Figure 9.

In the top row of Figure 9 the RNM and RRPFS values of experiments with 1000bar are shown. Due to the five cycle statistic, the statistical noise superposed to the data is too high to provide conclusions about the occurrence of misfires at these conditions. Nevertheless, reproducible ignition and flame propagation is detected at individual configurations representing the beneficial effect of dodecane blending.

With 800bar rail pressure RNM values of 0.2 are not exceeded indicating improved glow-plug ignition stability. Besides this, increased RRPFS values are calculated for all single injection strategies and split injection strategies with decreased time distance between both actuations. Thereby, a major improvement in comparison to experiments with 100% ethanol at the given rail pressure can be seen.

In the third and forth row of Figure 9 the statistical values of experiments with 600 and 400bar are given. It can be seen that below 600bar rail pressure no misfires were detected. Moreover, increasing RRPFS can be seen with increasing single injection actuation and decreasing time distance between split injections. Therefore, the border of glow-plug ignition stability is increased the by 200bar rail pressure in comparison to 100% ethanol experiments. Nevertheless, the rail pressure seems to be the major influence parameter for sufficient glow-plug ignition stability.

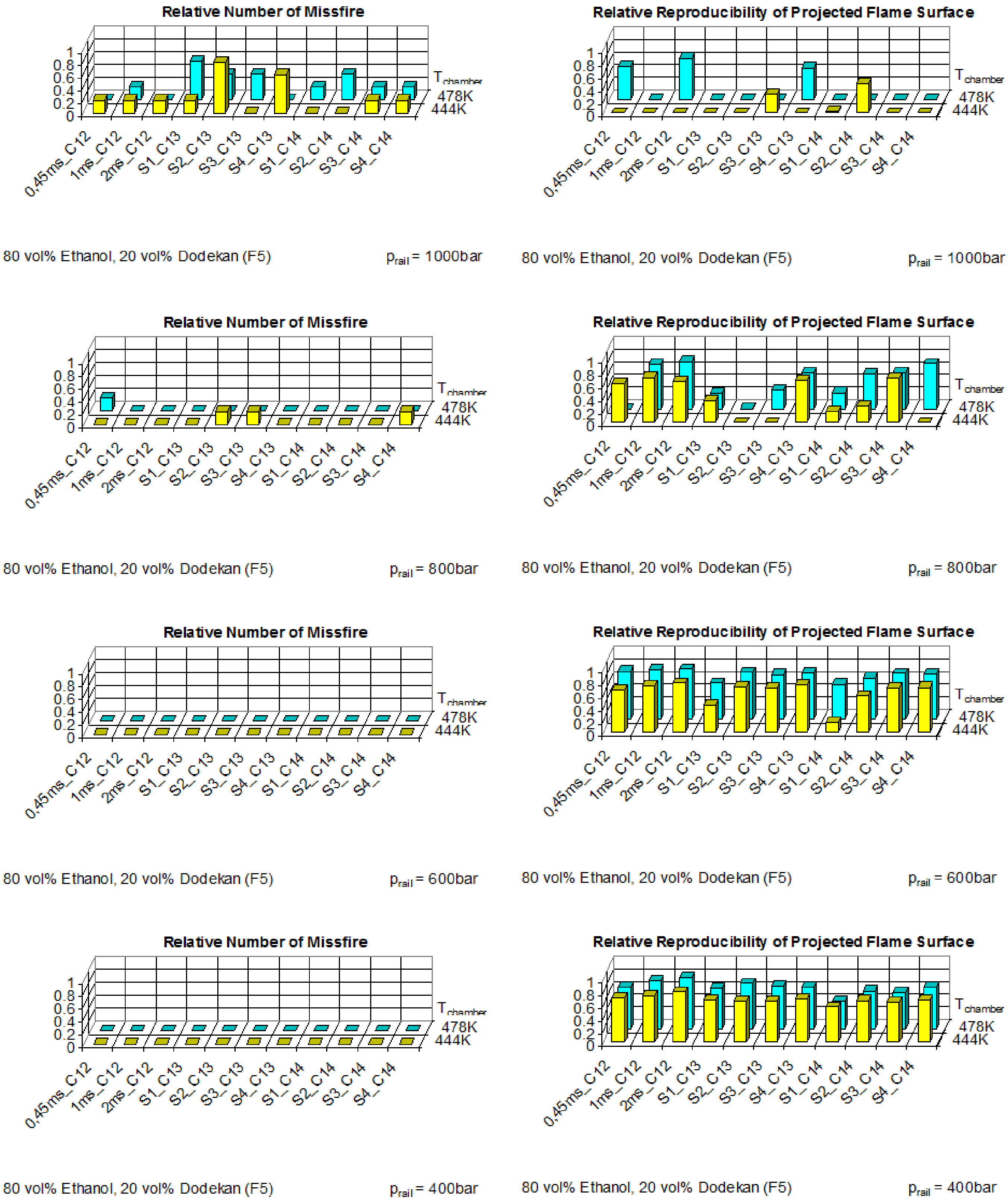

Figure 9 Statistical evaluation of glow-plug ignition stability with ethanol-dodecane mixture for varying rail-pressures

SUMMARY AND CONCLUSIONS

In this investigation the ignition behavior of ethanol and mixtures with high ethanol content is investigated in a high pressure and temperature vessel under Diesel engine relevant thermodynamic conditions. A pre-optimized targeting of the spray cone relative to the advanced ignition systems with ceramic glow-plug served a baseline configuration. Optical measurements are performed by high speed imaging of the fuel injection and ignition, and evaluated in terms of ignition and flame propagation. The high speed imaging technology furthermore enables to gain information on the statistical behavior of the ignition process and thus provides a direct assessment of the repeatability of the ignition and combustion process.

The investigated parameters are the fuel composition, injection strategy, rail pressure and chamber temperature. The results show that decreased rail pressure is the major impact parameters on glow-plug ignition stability improvement. It is assumed that this result is caused by decreased turbulent dissipation in the vicinity of the glow-plug surface. Moreover, the glow-plug ignition stability is improved by single injection strategies as the split of injector actuation decreases the time for sufficient ignition before flame extinction with injector closing. In comparison of split injection strategies no significant difference can be detected between strategies with pilot and main injection and strategies with equally distributed injections. Concerning the time distance between both actuations, a short time distance is advantageous as complete injector closing and flame extinction is inhibited. Nevertheless, reproducible glow-plug ignition of 100% could be achieved with all configurations at rail pressures of 400bar. The border if ignition stability could be increased to 600bar by fuel blending with 20 vol% dodecane.

Based on these results it is shown that glow-plug adaption can provide stable ignition conditions with ethanol blended fuels at ambient conditions related to passenger car cold start conditions. Moreover, major impact parameters and mechanism of ignition are identified.

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ACKNOWLEDGMENTS

This work was performed as part of the Cluster of Excellence "Tailor-Made Fuels from Biomass", which is funded by the Excellence Initiative by the German federal and state governments to promote science and research at German universities