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Introduction

1.1 Motivation

Since the first invention around 200 years ago, internal combustion engine based automobile-technology had experienced big advancements. Pressures of environmental problems due to air pollution, as well as a trend of world's shortage in oil energy supplies, demanded automobiles with a clean and efficient combustion. Automobile industries have been challenged to meet the emission-standards in order to win the market. These standards are ever more stringently implemented by groups of countries.

Example given here are in European countries, as part of the world's leading automotive industries. They adopted *EURO-norm* emission-standards. Norm-values for gasoline passanger cars (given in grams / km, for CO, HC, and NO_x, respectively) are 2.3, 0.2, 0.15 - which applied in *EURO-3* (affected per 2000), 1.0, 0.10, 0.08 - which applied in *EURO-4* (affected per 2005), and 1.0, 0.075, 0.06 – proposed to be applied in *EURO-5* (mid 2008). Similar stringent acts are also implemented in both USA and Japan. Comparison of norm-values among those countries can be found in **[Home]**.

Several improvements in engine technology have already been made parallel to the attempts to implement alternative substitutes of fossil fuels. Among these attempts are implementation of new concepts in engine combustion, such as Gasoline Direct Injection system and the development of *Homogeneous Charge Compression Ignition (HCCI)* combustion. The HCCI combustion process actually represents an adaptation of diesel combustion technology into the gasoline one.

In Gasoline Direct Injection systems, combustion takes place in an overall lean load. This can be realised by stratifying the fuel injection, i.e maintain the rich ignitable fuel/air mixture just around the tip of the spark-plug and keep other areas of the combustion chamber in the lean-state. Meanwhile in HCCI combustion systems, a homogeneous dilute mixture of fuel and air (plus additional recirculated combustion rest-gas) are compressed to higher pressure, leading to self-ignition diesel-like combustion.

The advancements above can not be separated from continuing research efforts on the internal engine combustion processes. Most of the research work is directed to produce further improvements in the combustion. Reliable diagnostic methods are required as a tool, which can provide a *better insight* about *what's really going on* in the combustion process being investigated. It is also necessary that the tool can probe the process without disturbing the ongoing process itself, as well as planar detection capability in order to extract spatially resolved information across the chamber where the process takes place.

Laser-Induced-Fluorescence (LIF) is one of the most used methods for such a purpose. A small amount of specific fluorescence-tracers, with known spectroscopic properties, is usually used as dopant for the non-fluorescing model-fuel. A beam of laser light is then applied resonantly to the characteristic- transition of the tracer molecules in order to excite them to certain excited states, which then deactivate back to the ground state by emitting light. This light is normally shifted to longer wavelengths, and is known as *fluorescence*.

Often normal regular gasoline is not used for such purposes, due to its content of multi unsaturated aromatic molecules, which strongly absorb the light. That is why, exciting the mixture will also lead to emission of their own characteristic fluorescence, which makes the interpretation of the required signal difficult.

Temperature and pressure are two of the most important physical variables in the engine combustion process. Since during the cyclical compression – expansion movement of the pistons, both of the variables are continuously changing accordingly. In the stratified combustion cycle, a spray-injection of fuel is done just before the ignition takes place. Therefore an inhomogeneous fuel-air distribution across the cylinder is created, which affects the combustion process during the next cycle-progression. This mixture-inhomogeneity will also induce inhomogeneity in temperature distribution.

These mixture-inhomogeneities can be detected spatially-resolved by laser-induced fluorescence (LIF). Due to molecular collisions of the excited molecules with other molecules in the mixture, the excited-state of the tracer molecules can be deactivated via a non-radiating pathway. This is known as *quenching*. Oxygen, which represent a component of air, is known as a strong quencher, as will be temperature.

Formaldehyde is known as an intermediate product in the combustion of the most hydrocarbons. The creation of formaldehyde happens in the early stage of combustion after ignition (known also as *cool-flame* period) and finally be consumed again before the combustion is completed. The presence of formaldehyde gas distribution in the combustion chamber can indicate areas of low-temperature combustion reaction [Coll]. Meanwhile as the process proceeds, the amount of formaldehyde gas is diminished. This diminishing is also accompanied by the rise of temperature. The areas of diminishing formaldehyde-concentration distribution is known as *hot-spots*, which can lead to the creation of knocking. Knocking is a condition of autoignition, which is accompanied by a strong acoustical pressure. This strong pressure can even lead to damages to the piston's surface as well as other metal parts of the engine.

Based on the above properties, many researchers have utilized the fluorescence of formaldehyde gas as a tracer for detecting the onset of knocking **[Hoff]**, for tracing and visualizing the flame propagation **[Blad]**, as well as a way for measuring temperature distribution in the combustion chamber **[Burk]**.

In order to be able to quantify the engine-internal mixture-formation process using fluorescence method, the loss of fluorescence signal due to quenching from both pressure as well as temperature should also be properly quantified. This quantification will then be used for correction purposes. For quantification purposes it is important to know the photophysical behavior of the fluorescence tracer against temperature as well as pressure.

In this thesis, it will be explored the possibility to use formaldehyde gas as a dopant, which would be used to quantify the state of the mixture formation process in the engine before the ignition takes place.

This work shall check if it is possible, to measure the temperature distribution and the fuel distribution simultaneously. It would be an advantage, that information on temperature distributions can also be utilized for the quenching correction due to temperature. Meanwhile quantification of the state of mixture formation can be obtained accordingly. And there is the possibility that both of the measurements can be used to measure the distributions in 2D manner, known as planar LIF (abbreviated as PLIF) measurement.

1.2 Outline of the thesis

Explanations given in this thesis will be divided into the following chapters.

In Chapter-1 , the motivations and ideas behind this thesis will be described, as well as their descriptions' outline. It will then followed by Chapter-2, in which the fundamentals of engine operating process are described. It comprises underlying principle of combustions, compression-expansion mechanism, ignition, and influence of some thermodynamic state variables to the combustion efficiency as well as pollutant formation.

Chapter-3 describes the fundamental processes used in the diagnostic using LIF, i.e. generation of LIF signal, and other factors that influence the resulting signal. *Quenching*, i.e. loss of fluorescence signal due to non-radiative pathways during the deactivating processes, of the formaldehyde to foreign gases commonly encountered in the engine combustion process is also discussed. This will lead to understanding how this tracer substance behaves to such gases.

Chapter-4 is specifically devoted to discuss the behaviour of the dopant tracer used, i.e. formaldehyde. Spectroscopy as well as photophysical properties of the tracer material used is given. Formaldehyde is normally available in the gas phase, and obtained by heating paraformaldehyde, which is available in powder form. For the combustion diagnostics using tracers, the intended tracer should have been able to be mixed into the fuel. Methods to prepare formaldehyde to be used as fluorescence dopant tracer as well as its concentration determination in the fuel mixture will be briefly discussed. Principle of two-lines thermometry using formaldehyde will also be included. This method offers advantage for the implemention into planar measurement techniques for temperature distribution determination.

Discussions will continue in Chapter-5, in which all about experimentation is being described. Experimental set up, gas handling system, as well as approaching methods adopted for data acquisition and analyses are discussed.

One way to quantify the quenching process of the fluorescence is by using fluorescence lifetime measurement. Several principles in fluorescence lifetime measurement will be discussed. A method proposed by Demas which is known as *Rapid Lifetime Determination* (abbreviated as *RLD*) will be adopted during the work. This method is based on the ratio of the two time-gated images, and offers advantages to be implemented for planar imaging purposes.

Experimental implementing two-line thermometry using formaldehyde is also described.

Meanwhile the applicability of formaldehyde as fluorescence tracer to be implemented to measure the state of mixture formation will also being discussed. The approach that was first introduced by Reboux will be tested for its applicability using this tracer. This approach is well known as ***F****uel-****A****ir-****R****atio* ***L****aser-****I****nduced-****F****luorescence*, abbreviated as ***FARLIF***.

Results of the experiments being done, as well as the related discussions, will be given in Chapter-6. It deals with the investigations on spectroscopic as well as photophysical behaviour of formaldehyde. Correction-factors applied to the attenuated local fluorescence of the detected signals are described. These attenuations are due to local inhomegeneities of the temperature as well as the pressure. These factors are affected by dependencies of the *absorption cross section* σ and *fluorescence yield* ϕ on both of the environmental variables above. It is then continued with the implemention of formaldehyde as tracer for the fuel-air ratio measurements. Possible factors that influence the accuracy as well as precision of the proposed method will be discussed.

The explanation is ended by Chapter-7, in which a general discussion that lead to the summary of the work is given. Possible things that are necessary to be implemented for future works will be given as outlook.

2

Engine Combustion Fundamentals

Since the first gasoline engine introduction by N.A. Otto (1832 – 1891), automotive engines have experienced large improvements, in terms of engine efficiency and reduced pollutant formation. These improvements are results of continuing research on the combustion system as well as related supporting fields, such as combustion chemistry, physics, electronic control systems, etc.

In the following sections topics related to generation of power from combustion of hydrocarbon (fuel) will be briefly described. Components that make up engine combustion systems as well as terminologies that are used to parameterize the combustion process will also be described. It is then continued by description on the related thermodynamic state variables that govern the combustion process. Understanding of these variables is important for the diagnostics purposes, in order to get an exact quantification of the combustion related quantities.

Large parts of the descriptions below are devoted to the spark ignition engine. A description about the HCCI combustion system will also be given in Section 2.7. This combustion system is promising to be applied in practice in the future.

Subjects described in this section refer mostly to **[Heyw]**, and from other additional references, as being stated.